# USE OF OPEN SOURCE INFORMATION AND COMMERCIAL SATELLITE IMAGERY FOR NUCLEAR NONPROLIFERATION REGIME COMPLIANCE VERIFICATION BY A COMMUNITY OF ACADEMICS

A Dissertation

by

ALEXANDER SOLODOV

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

August 2007

Major Subject: Nuclear Engineering

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## ABSTRACT

Use of Open Source Information and Commercial Satellite Imagery for Nuclear Nonproliferation Regime Compliance Verification by a Community of Academics. (August 2007)

Alexander Solodov, M.S., Ural State Technical University

Chair of Advisory Committee: Dr. William S. Charlton

The proliferation of nuclear weapons is a great threat to world peace and stability. The question of strengthening the nonproliferation regime has been open for a long period of time. In 1997 the International Atomic Energy Agency (IAEA) Board of Governors (BOG) adopted the Additional Safeguards Protocol. The purpose of the protocol is to enhance the IAEA's ability to detect undeclared production of fissile materials in member states. However, the IAEA does not always have sufficient human and financial resources to accomplish this task. Developed here is a concept for making use of human and technical resources available in academia that could be used to enhance the IAEA's mission.

The objective of this research was to study the feasibility of an academic community using commercially or publicly available sources of information and products for the purpose of detecting covert facilities and activities intended for the unlawful acquisition of fissile materials or production of nuclear weapons. In this study, the availability and use of commercial satellite imagery systems, commercial computer codes for satellite imagery analysis, Comprehensive Test Ban Treaty (CTBT)

verification International Monitoring System (IMS), publicly available information sources such as watchdog groups and press reports, and Customs Services information were explored. A system for integrating these data sources to form conclusions was also developed. The results proved that publicly and commercially available sources of information and data analysis can be a powerful tool in tracking violations in the international nuclear nonproliferation regime and a framework for implementing these tools in academic community was developed.

As a result of this study a formation of an International Nonproliferation Monitoring Academic Community (INMAC) is proposed. This would be an independent organization consisting of academics (faculty, staff and students) from both nuclear weapon states (NWS) and non-nuclear weapon states (NNWS). This community analyzes all types of unclassified publicly and commercially available information to aid in detection of violations of the non-proliferation regime. INMAC shares all of this information with the IAEA and the public. Since INMAC is composed solely by members of the academic community, this organization would not demonstrate any biases in its investigations or reporting.

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# CHAPTER I

# INTRODUCTION AND LITERATURE REVIEW

## I.A. Objective

Today the proliferation of nuclear weapons is a great threat to world peace and stability. Recent discoveries of several clandestine nuclear weapons programs in the countries that are signatories of the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) raises more concerns about the future of the nuclear non-proliferation regime and demonstrates an essential need for strengthening the regime. An additional concern is that a country after succeeding in developing a covert nuclear program may sell a weapon to a non-state actor or a terrorist group.

In order to address all these concern, the International Atomic Energy Agency (IAEA), which historically was only performing verification of the member states' compliance with their own declarations, is now expanding the use of open sources of information and commercial satellite imagery in order to enhance its ability to detect undeclared production of fissile material. However, the Agency does not always have sufficient human and financial resources to accomplish this task. The objective of this research was to study the feasibility of an academic community using commercially or publicly available sources of information and products for the purpose of detecting covert facilities and activities intended for the unlawful acquisition of fissile materials or

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This dissertation follows the style of *Nuclear Technology.*

production of nuclear weapons. The availability and use of the following main potential sources of information were explored:

1. commercial satellite imagery systems,
2. commercial computer codes for satellite imagery analysis,
3. Comprehensive Test Ban Treaty (CTBT) verification International Monitoring System (IMS),
4. publicly available information sources such as watchdog groups and press reports, and
5. Customs Services information.

Another important task is extraction of the useful pieces from selected sources and combining them into a meaningful compilation. Collecting, organizing, determining associations, tracking, and drawing conclusions from a wide variety of information types can be a daunting task [1]. An algorithm for effective data integration was defined and proposed as a part of this project. This routine would allow segregation of information by the relation to the particular stage of the country's weapons program and effectively estimating state's covert activities progress.

As a part of this research project, forming an International Nonproliferation Monitoring Academic Community (INMAC) is proposed. This would be an independent organization consisting of academics (faculty, staff and students) from both nuclear weapon states (NWS) and non-nuclear weapon states (NNWS). This community would analyze all types of unclassified publicly and commercially available information to aid in detection of violations of the nonproliferation regime. INMAC would share all of this information with the IAEA and the public. Since INMAC would be composed solely by members of the academic community, this organization should be less prone to demonstrate any biases in its investigations or reporting.

### I.B. Possible Proliferation Routes

There are several routes that a country dedicated to obtaining nuclear weapons can take. Manufacturing nuclear weapons, shown schematically in Fig. 1, is a complex and difficult process. It can be divided into three basic stages: (1) acquisition of special nuclear material (SNM), (2) weaponization of the SNM using non-nuclear components, (3) production of a delivery system for the weapon. The first, and most difficult, is the production of the special nuclear materials [Pu, $^{233}U$, or highly enriched uranium (HEU)] that are the heart of a nuclear warhead. SNM is composed of $^{239}Pu$, $^{233}U$, or $^{235}U$. These materials are called fissile materials, because their nuclei have a high probability to split, or fission, after absorption of a neutron regardless of the neutron energy. Basic fission weapons are made using some combination of fissile materials. Fissioning of those isotopes is accompanied by the release of tremendous amounts of energy and additional neutrons to sustain the chain reaction; this allows the use of those isotopes in nuclear reactors and gives nuclear weapons huge amounts of explosive power.

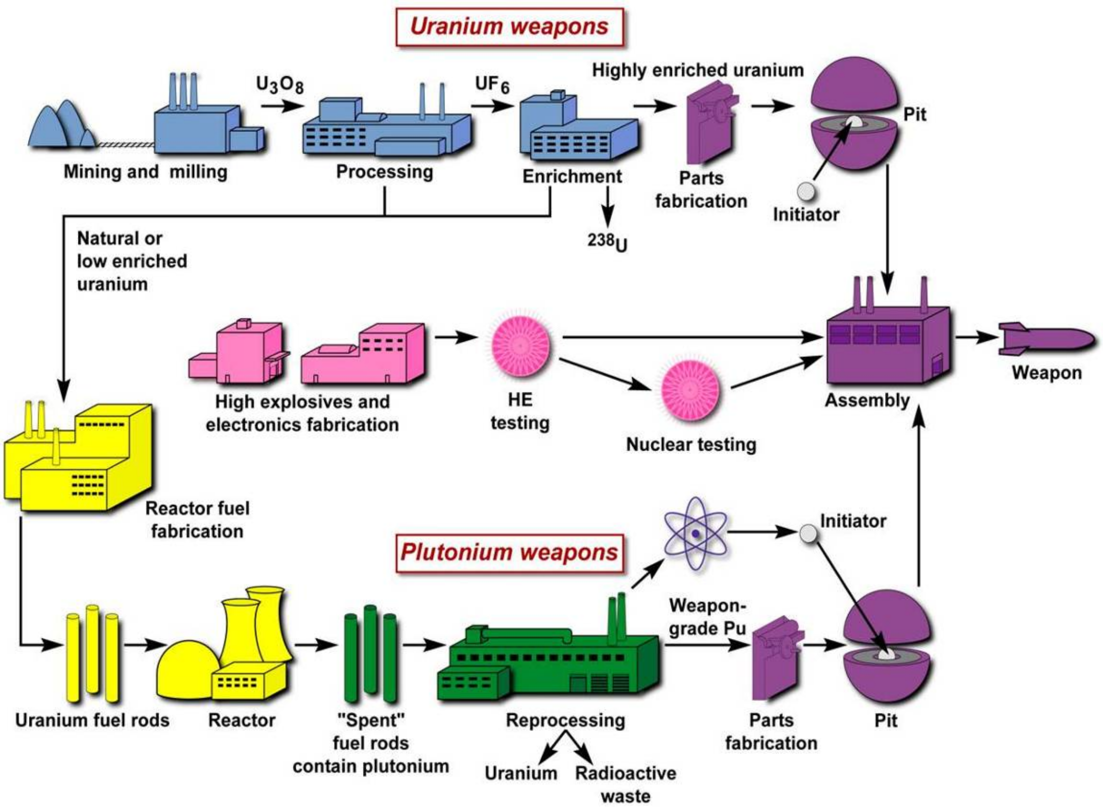


Fig. 1. Technical Routes to a Nuclear Capability.

The magnitude of the mass of the fissile material needed to sustain a chain reaction in an explosive device is called the critical mass and is measured in kilograms for plutonium or $^{233}U$ and tens of kilograms for enriched uranium (the exact size of critical mass depends on the conditions of the chain reaction initiation: pressure, purity of the material, density etc.). Fortunately, from the nonproliferation standpoint, special nuclear materials are not readily available in the nature and obtaining the necessary quantities of material requires a full-scale industrial process that uses advanced scientific technologies. One of the fathers of U.S. nuclear bomb, Edward Teller, said once: “As soon as the country will be able to obtain nuclear material in necessary amount, creation of the nuclear weapon will be a question of several months" [2].

There is a principal difference in obtaining the types of material in the required quantity and quality:

1. $^{235}U$ exists in nature mixed with another uranium isotope ($^{238}U$) in a very low mass concentration of about 0.7%. A special separative technology is required for enrichment of uranium in the $^{235}U$ isotope to concentrations close to 90% (or at least about 20%). All of the proven technologies for uranium enrichment are based on a small (0.4%) mass difference between uranium isotopes.
2. Plutonium is derived from the naturally occurring $^{238}U$ isotope, which cannot be used directly in a nuclear weapon. Plutonium is created following a neutron capture by $^{238}U$ and two beta-minus decays of intermediate nuclei. Therefore plutonium production requires irradiation of natural or depleted uranium with a high neutron flux and chemical separation of plutonium from uranium and fission products.
3. Similar to plutonium, $^{233}U$ for weapons can be derived from the naturally occurring thorium ($^{232}Th$) isotope, which cannot be used directly in a nuclear weapon. $^{233}U$ is created following a neutron capture by $^{232}Th$ and two beta-minus decays of intermediate nuclei. Therefore $^{233}U$ production requires irradiation of natural thorium with a high neutron flux and chemical separation of $^{233}U$ and thorium afterwards. However, unlike

plutonium production by neutron irradiation, the irradiation of thorium also produces another uranium isotope ($^{232}U$) which decays to highly radioactive daughter products that complicate the use of $^{233}U$ for producing nuclear weapons. While this route is similar to the plutonium production route shown in Fig. 1, it is more complicated since thorium can not be made critical thus requiring an enriched uranium or plutonium seed fuel to irradiate the thorium and since the presence of $^{232}U$ complicates the handling of the $^{233}U$ without remote operations. For these reasons, this route is not considered further herein.

The second stage is weapon assembly. To make the enriched uranium or plutonium into a weapon, various additional components must be added:

1. chemical explosives (or in the case of gun-type weapons, propellants) to assemble the nuclear material into a super-critical mass that will sustain an explosive chain reaction,
2. nonfissile materials to reflect neutrons and tamp the explosion,
3. electronics and detonators to trigger the explosives,
4. a neutron generator (called an initiator) to start the nuclear detonation at an appropriate time, and
5. associated command, control, and security circuitry.

The third stage in developing a nuclear weapons capability is integrating the weapon with a delivery system and preparing for its use. The choice of a delivery method (aircraft, missile, etc.) is strongly dependant on the size of the weapon: the smaller the weapon, the more advanced delivery vehicle can be used. In the case of a state-proliferator, there is a high probability that it will choose the path of modification of its existing ballistic missile or aircraft technologies or it will try to acquire the necessary expertise with external help.

Based on this information a conclusion can be made that a potential proliferator has three options for acquiring fissile material needed for a nuclear weapon: (1) purchase or theft, (2) diversion from civilian nuclear activities in violation of IAEA safeguards, or (3) indigenous production in unsafeguarded facilities.

Indigenous production of weapon-grade nuclear material requires a large, complex, and expensive set of specialized facilities, and the relevant facilities therefore represent principal “chokepoints” for controlling nuclear proliferation. Many different approaches to producing nuclear materials are available, depending on what nuclear materials a proliferator starts with, what access it has to dual-use or nuclear-specific technologies, and what cost it is willing to bear to acquire proscribed technologies on the black market. Various approaches also place specific demands on the proliferator’s technology base, infrastructure, and expertise, and pose different operational difficulties and risks of detection once acquired.

## I.C. The History of the Nonproliferation[†] Regime

The history of the nuclear nonproliferation regime, and its evolution to the form in which it exists now, is more than 30 years old. After appearance of the first two nuclear powers (the United States of America and the Soviet Union), the world

[†] Non-Proliferation and Nonproliferation are interchangeable terms.

community did not immediately realize the importance of stopping or freezing the process of new nuclear weapon states arising. Not until the end of the 1960s, when the group of countries possessing nuclear weapon had grown to five members, did the world community start to work on co-operational measures to prevent the spread of nuclear arms and create an international legal system for the nonproliferation regime. The result of these efforts led to the Treaty on the Non-Proliferation of Nuclear Weapons (NPT), which was open for signing on July 1, 1968 and came into force on March 5, 1970 [3]. The NPT though is mainly a philosophical document setting the baseline for the nuclear nonproliferation regime. Creation of the international system of mechanisms, norms and procedures followed after the creation of the treaty. All together, combined with the international safeguards and export controls systems, this formed the regime of nonproliferation of the nuclear weapons.

*I.C.1. The Treaty on the Non-Proliferation of Nuclear Weapons*

The NPT represents the world's single most important multilateral nuclear arms control agreement and it remains the most successful exemplar of arms control [4]. As of today the NPT has 188 member states and only 3 countries are not signatories of the Treaty: India, Pakistan and Israel. There is one country that used its right to withdraw from the Treaty: the Democratic Peoples Republic of Korea (DPRK). Five of the member states are nuclear weapon states (NWS): China, France, the Russian Federation, the United Kingdom, and the United States. All others are non-nuclear weapon states (NNWS).

The NPT consists of 11 articles:

1. **Article I** states that NWS are obliged not to transfer to NNWS nuclear weapons, other nuclear explosives and control over such devices. Also NWS are obliged not to encourage or assist any of NNWS to acquire nuclear weapons;
2. **Article II** states that each NNWS party undertakes not to receive or manufacture nuclear weapons or explosives;
3. **Article III** outlines measures for the use of IAEA nuclear safeguards. Each NNWS will accept safeguards to be negotiated for the exclusive purpose of verifying the fulfillment of the party's NPT obligations.
4. **Article IV** guarantees the right of all states-parties to research, develop and produce nuclear energy for peaceful purposes. All the state parties have a right to exchange information and equipment (with other states) for peaceful uses of nuclear energy.
5. **Article V** states that each party of the treaty shall undertake measures to ensure to make available to NNWS parties any potential benefits of the application of "peaceful nuclear explosions". NNWS parties shall be able to obtain such benefits through special agreements and an appropriate international body with adequate representation of non-nuclear-weapon states.
6. **Article VI** provides that "each of the Parties to the Treaty undertakes to pursue negotiations in good faith on effective measures relating to

cessation of the nuclear arms race at an early date and to nuclear disarmament, and on a Treaty on general and complete disarmament under strict and effective international control."

7. **Article VII** provides that any group of states has the right "to conclude regional treaties in order to assure the total absence of nuclear weapons in their respective territories".

8. **Article VIII** provides for NPT amendment procedure.

9. **Article IX** provides the following:

- any state may accede to the NPT at any time
- ratification by signatory states shall be deposited with the U.S., the USSR and the U.K. (Depositary Governments)
- the treaty shall be entered into force upon ratification by the three depositary states and forty other states
- for states depositing their instruments of ratification after the NPT enters into force, it becomes applicable on the date of their accession
- depositary governments shall promptly inform all states of: the date(s) of each signature(s), date(s) of deposit(s) of instruments of ratification, the date of receipt of any request for convening a conference and all other notices.

10. **Article X** provides the withdrawal case: "Each Party shall in exercising its national sovereignty have the right to withdraw from the Treaty if it decides that extraordinary events, related to the subject

matter of this Treaty, have jeopardized the supreme interests of its country. It shall give notice of such withdrawal to all other Parties to the Treaty and to the United Nations Security Council three months in advance. Such notice shall include a statement of the extraordinary events it regards as having jeopardized its supreme interests." Also 25 years after the treaty enters into force a conference shall be convened to decide whether the treaty shall continue indefinitely, or shall be extended for an additional fixed period of time.

11. **Article XI** establishes that text of the treaty in English, Russian, French, Spanish and Chinese, equally authentic, shall be deposited in the archives of the Depositary Governments. Certified copies should be transmitted to the newly acceding states [3].

*I.C.2. International Atomic Energy Agency*

The IAEA (often referred to simply as "the Agency") was formed in 1957. The main goal of the Agency is assistance to the peaceful use of nuclear energy and assurance that it is not used for warfare. This goal was stated in Article II of the IAEA Statute. According to Article III of the Statute, the main functions of the IAEA are:

1. to promote scientific and research work and development of the use of atomic energy for peaceful purposes;
2. to provide services, materials, equipment and technical means;
3. to contribute to the exchange of scientific and technical information and specialists;

4. to provide safeguards; and
5. to establish norms of safety and health protection.

The formation of the IAEA was a consequence of the “Atoms for Peace” speech to the United Nations (UN) by President Dwight D. Eisenhower which promoted the use of atomic energy for peaceful purposes.

*I.C.3. Safeguards Regime Evolution*

The history of the international safeguards regime is more than 40 years old and it has many stages of evolution. The overall progress of the safeguards regime is presented in Fig. 2. Major documents, dates, and covered areas of nuclear fuel cycle are described in this section.

The first safeguards regime appeared almost 10 years earlier than the NPT. The first regulating document was INFCIRC/26 [5] issued in 1961. It was a first attempt to set the list of facilities and materials to be put under safeguards control. Basically, it covered low-powered reactors (less than 100 MW), most of which were research reactors.

In 1962, the Agency started inspections of low-powered reactors, but soon the number of more powerful reactors started to increase rapidly. By 1963, it became clear that the safeguard system should be spread over reactors of all power levels. In 1965, the first revision of INFCIRC/66 was adopted. This document was applicable to all reactors. However, it did not consider facilities like enrichment plants, fuel fabrication plants and reprocessing plants. In 1968, the final version of the document numbered INFCIRC/66 Rev.2 [6] was adopted. This system is still applied to a small number of facilities around the world. In this document, the definition of 'principal nuclear facilities' appeared which related to types of facilities other than reactors, which may produce, process, or use safeguarded nuclear materials.

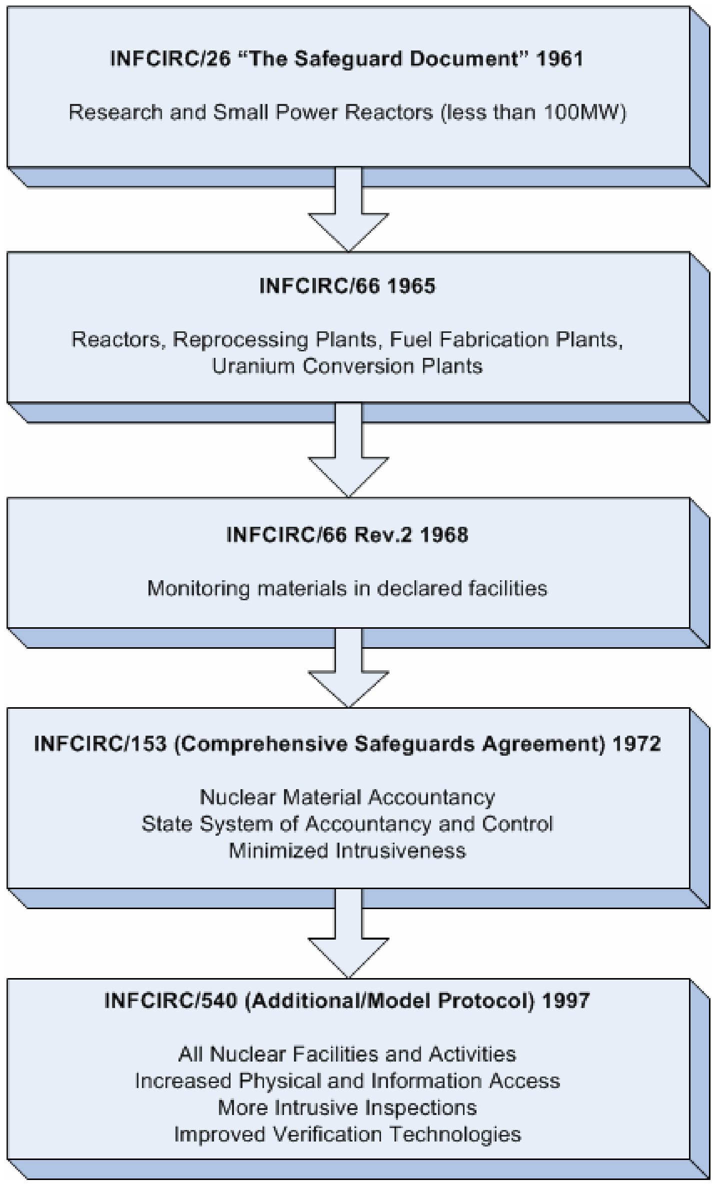


Fig. 2. The Historical Progression of the Safeguards Regime [7].

By the time the NPT was signed by the first parties a new system was needed which would cover not only particular materials or equipment but all nuclear activities of the state-party of the NPT. Such a system was actively developed by a committee consisting of the USA, USSR, and the United Kingdom. INFCIRC/153 [8] detailed a form of agreement between the IAEA and States (parties of the NPT) and was called the 'Comprehensive Safeguards Agreement'. This system has been a standard for the last quarter of the last century and is still implemented in many countries today.

The main way of providing safeguards guarantees was accountancy of special nuclear materials. Each member state must create an accounting system and report to the IAEA. Measures of the Agency to control nuclear material include (1) the use of seals, surveillance equipment and other devices to trace the transfers of material and its movement and (2) confirming material balance at the particular facility. IAEA inspectors, having special privileges and immunities, periodically attend facilities to verify the physical inventory of material, changes to that inventory, the accuracy of the reports, and to take samples to be analyzed by the Agency. The results of the inspection are presented to the State by the Agency. If there is some evidence that some amount of material was diverted for non-peaceful use, then the IAEA Director General presents a report to the IAEA Board of Governors (BOG). If the BOG decides that the IAEA cannot verify the fact of diversion by itself, it reports to the UN Security Council.

The INFCIRC/153 system was a product of difficult negotiations between those industrial NNWS which desired as little interference in the operation and cost of their nuclear power system as possible, and those states that attempted to create a verification system to give effective early warning of any diversion from a civil fuel cycle. One consequence was that its focus was on the misuse of declared materials and known facilities, rather than searching for undeclared materials and plants. Another was that most of its inspection effort was focused upon Canada, Germany and Japan, even though by the 1980s they appeared to be unlikely candidates as prospective nuclear proliferators. A third was that "NWS made 'voluntary offers' to place elements of their civil industry under IAEA safeguards in order to engage in an exercise of 'equality in misery' with industrial NNWS in shouldering the burden of accepting IAEA safeguards" [9].

After the discovery of the clandestine nuclear weapon program in Iraq during the Gulf War in 1991, the IAEA undertook intensive efforts on strengthening the safeguards regime and preventing the development of covert weapon programs. In 1993, the BOG adopted the so-called "Program 93+2" [10] on the creation of a more efficient and cost-effective safeguards regime. During the work on this program, it was confirmed that among the measures used as a part of existing legal authority should be:

1. obtaining more detailed information on facilities, where nuclear materials were ever located or are planned to be located at any time;
2. extensive use of undeclared inspections;
3. environmental sampling in the places where inspectors have access to; and
4. use of improved technologies for distant monitoring of nuclear materials transfers.

For the purpose of further strengthening the safeguards regime in May of 1997, the Border of Governors adopted a voluntary Additional Protocol (INFCIRC/540) [11] to the IAEA Safeguard Agreements with parties to the NPT. The model protocol outlined four key changes that must be incorporated in each NPT state party's safeguards agreement when the Additional Protocol is signed:

1. The amount and type of information that states will have to provide to the IAEA is greatly expanded. In addition to the current requirement for data about nuclear fuel and fuel-cycle activities, states will now have to provide an "expanded declaration" on a broad array of nuclear-related activities, such as "nuclear fuel cycle-related research and development activities not involving nuclear materials" and "the location, operational status and the estimated annual production" of uranium mines and thorium concentration plants. All trade in items on the Nuclear Suppliers Group trigger list will have to be reported to the IAEA as well.
2. The number and types of facilities that the IAEA will be able to inspect and monitor are substantially increased beyond the previous level. In order to resolve questions about, or inconsistencies in, the information a state has provided on its nuclear activities, the new inspection regime provides IAEA with "complementary", or preapproved, access to "any location specified by the Agency," as well as all of the facilities specified in the "expanded declaration." By negotiating an Additional Protocol, states will, in effect, guarantee the IAEA access on short notice to all of

their declared (and, if necessary, undeclared) facilities in order "to assure the absence of undeclared nuclear material and activities."

3. Inspectors should be guaranteed to be able to obtain multi-entry visas within a month and have access to modern means of communication.
4. The Additional Protocol provides the IAEA the right to use environmental sampling during inspections at both declared and undeclared sites. It further permits the use of environmental sampling over a wide area rather than being confined to specific facilities.

As of November of 2006, the Additional Protocol was signed by 110 nations. Though the Additional Protocol greatly strengthens the IAEA's ability to verify that NNWS that are parties to the NPT use nuclear facilities only for peaceful purposes, it cannot prevent a determined state from acquiring a nuclear weapons capability [12].

### I.D. Nonproliferation Regime Successes

The main success of the NPT is that the Treaty created and established an international legal base for the nuclear nonproliferation regime and created beneficial stimulus for those countries that want to remain free of nuclear weapons [13]. The NPT, and the atmosphere in the world created by the Treaty, played one of the main roles in the fact that after the bombing of Hiroshima and Nagasaki, nuclear weapons were never again used in combat.

The Treaty became the largest (in number of parties) arms control treaty. It has 188 member states, 183 of which are NNWS. Originally, the NPT was negotiated to be in force for 25 years (until 1995). In 1995, the NPT Review Conference was held and the Treaty was extended indefinitely.

The overwhelming majority of states decided that their security interests are better served by not having nuclear weapons. Some states gave up nuclear weapons capabilities not even starting weapon programs; others reversed themselves at different stages of their quest for a nuclear weapon capability. Canada was the first state that had the capacity to make nuclear arms to renounce such a capacity. Among others, that under different circumstances gave up their ambitions or capabilities, are Australia, Argentina, Belarus, Brazil, Italy, Kazakhstan, Libya, South Africa, Sweden, Switzerland, and Ukraine.

Historical results of nuclear weapon programs of different countries are presented in Fig. 3. In the 1960s, 23 countries had weapons, were conducting weapons-related research, or were discussing the pursuit of nuclear weapons: Argentina, Australia, Brazil, Canada, China, Egypt, France, India, Israel, Italy, Japan, Norway, Romania, South Africa, Spain, Sweden, Switzerland, Taiwan, United Kingdom, United States, USSR, and Yugoslavia. In the 1980s, 19 countries had weapons or were conducting weapons-related research: Argentina, Brazil, Canada, China, France, India, Iran, Iraq, Israel, Libya, North Korea, Pakistan, South Africa, South Korea, Taiwan, United Kingdom, United States, USSR, and Yugoslavia. In 2005, in addition to the 8 states with nuclear weapons, Iran and North Korea are suspected of having active nuclear weapons programs [12].

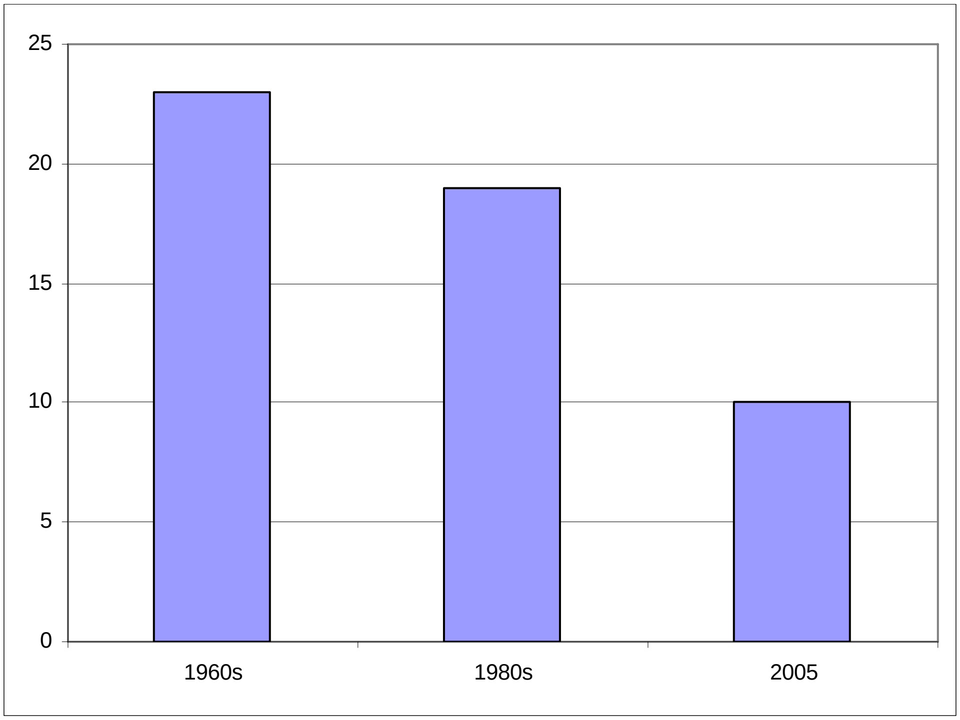


Fig. 3. Countries with Nuclear Weapons or Programs (Number of Programs) [12].

South Africa's decision to destroy its six nuclear explosive devices as well as its weapons infrastructure and then join the NPT as a NNWS was unprecedented. It reflected changes in political dynamics and threat perceptions and also gave an example to others. Another special case was created by the three successor states to the USSR: Belarus, Kazakhstan and Ukraine. Those countries did not pursue nuclear weapon capabilities, but accidentally became de facto NWS after the breakup of the Soviet Union, which left nuclear warheads on their territory. They did not have either resources or capabilities to maintain a status as a nuclear-weapon state. They agreed to the removal of former Soviet nuclear weapons from their territory by a combination of financial inducements, security guarantees, and political considerations [4].

Fig. 4 shows the timeline for the number of countries with nuclear weapons. As can be seen from this graph, the number of nuclear weapon states grew rapidly during the first 25 years after the test of the first nuclear device. After the NPT came into force in 1970 the curve sharply leveled off and turned closer to a flat line until the recent nuclear weapons tests by Pakistan and the DPRK. This plot is another example in favor of the arguments about successes of NPT, but it also raises a question if the world is entering a new era of proliferation.

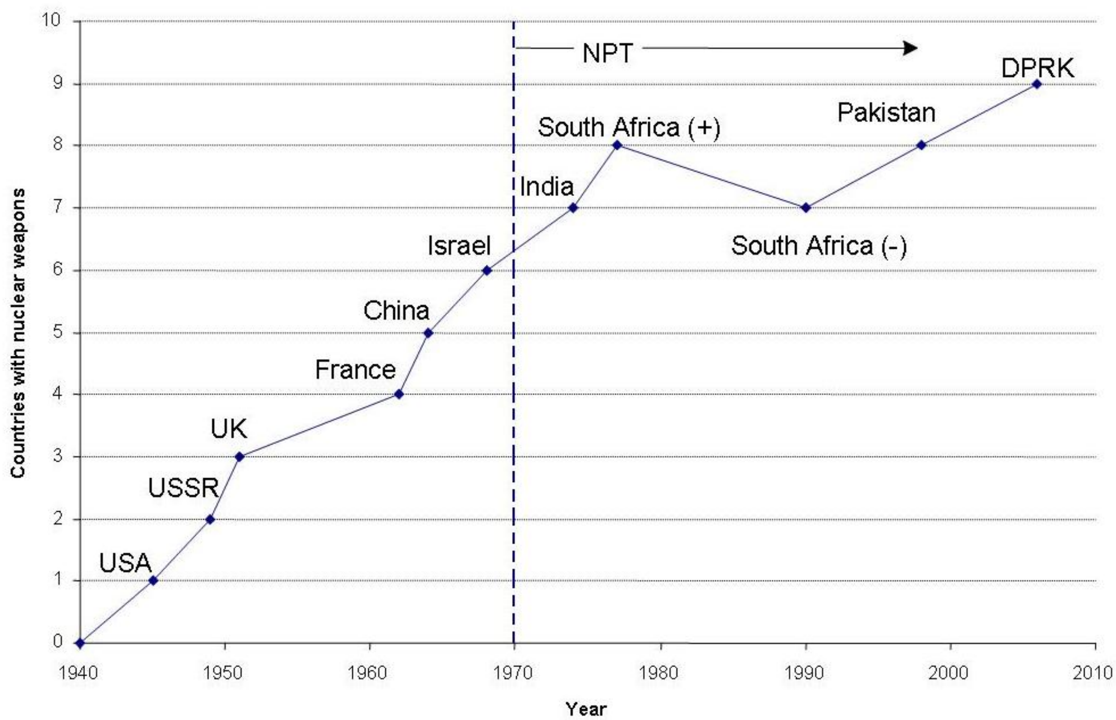


Fig. 4. Historical Progression of the Number of Countries with Nuclear Weapons.

As another measure to prevent the emergence of new NWS was the creation of a concept of nuclear-weapons-free zones (NWFZs). NWFZs have become to be recognized by the international community as a part of a phased approach to the process of nuclear arms controls and disarmament. In this regard, all existing NWFZ arrangements have a number of common characteristics:

1. a legal obligation to place all nuclear material and installations under full-scope IAEA safeguards;
2. to clearly demarcate the geographic limits of the zone of application in the territories of member states;
3. to specify the obligations, rights and responsibilities of contracting and protocol parties;
4. to promote international cooperation in the peaceful applications of nuclear energy under safeguards; and
5. to give indefinite duration to the NWFZ treaties.

In contrast to the NPT, NWFZs do not permit the "stationing" of nuclear weapons on the territories of states parties or "nuclear sharing"[‡] arrangements among NWS and NNWS. Currently more than 100 NNWS are parties to NWFZ treaties [4].

The NPT became a core, around which other multi-region and international mechanisms and agreements were created to help nuclear nonproliferation including:

1. Nuclear Suppliers Group [14],
2. Zangger Committee [15],
3. Convention of physical protection of nuclear materials [16],
4. Treaties on creation of nuclear-free zones in Latin America, the South Pacific, South-Eastern Asia and Africa [17, 18, 19, 20],

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‡ Under "nuclear sharing" agreements besides stationing of nuclear weapons on the NNWS territory, the control over them may also be transferred to the NNWS.

5. bilateral Argentine-Brazil verification organization [21], and
6. others.

With the help of the NPT it became possible to create a comprehensive safeguards regime. The purpose of this regime is to prevent nuclear materials used in peaceful programs to be transferred to any military program and to be used for the fabrication of a nuclear weapon of any kind. The safeguards regime is being improved constantly and now it is the most broad and technically advanced international control and verification system.

Unanimous adoption by the UN Security Council of the resolution 1540 (2004) [22], allowing the creation of effective barriers preventing nonstate organization (terrorists) from obtaining weapons of mass destruction including their components or means of delivery, was another big success for the nonproliferation regime. Resolution 1540 requires all states to “establish, develop, review and maintain appropriate effective national and trans-shipment controls” and “border controls” to prevent proliferation of nuclear, chemical, and biological weapons and their means of delivery. States must enact “appropriate laws and regulations to control export, transit, trans-shipment and re-export” of materials that would contribute to proliferation. “The primary advantage of the resolution over treaties addressing similar matters is that it is binding on all U.N. member states, including those outside the scope of the nonproliferation regime and those non-nuclear states that serve as reexport and manufacturing points in the proliferation network” [12].

Recently another international instrument was added to the list of measures taken by the world community to prevent the proliferation of weapons of mass destruction. The Proliferation Security Initiative (PSI) was declared by President George W. Bush in May of 2003 [23]. The initiative aims to stop shipments of biological, chemical, and nuclear weapons, as well as missiles and goods that could be used to deliver or produce such weapons, to terrorists and countries suspected of trying to acquire WMD. Initiative participants intend to carry out cargo interdictions at sea, in the air, or on land. PSI is limited solely to seizing shipments of WMD and dual-use goods (items that have both civilian, peaceful purposes and that can be used to make weapons) to those countries and nonstate actors viewed as threats by PSI participants. Today 15 states have joined this initiative and more than 60 states have agreed to provide assistance. The initiative goals are: detection, prevention and interdiction of unlawful transition of WMD related materials, including elimination of the existing "black market" of those materials.

An important conclusion that can be made as a result of the international consensus against the proliferation of nuclear arms and the more than 30-year history of the NPT is the appearance and development of a "nonproliferation culture and mentality". Almost all bilateral or multilateral talks on world security include discussions of nuclear nonproliferation problems, often those questions are central on the program [24]. Even if a country chooses to acquire nuclear weapons it has to be done secretly and covertly, which makes it much harder and more expensive. If the secret program is discovered, it is likely a violation of international laws and norms and can result in sanctions or even military actions.

**I.E. Nonproliferation Regime Difficulties and Failures**

One of the main issues, creating confrontation since the NPT's entry into force is the problem of nuclear arsenal reduction and eventual elimination by NWS as stated in Article VI of the Treaty. Even though there are some significant efforts by the US and Russia on cutting their arsenals, the two countries still have tremendous amounts of nuclear weapons. There probably will be more reductions in the future, but their complete elimination is very unlikely. Also, other NWS (China, France and Great Britain) have no intentions on stockpile reduction, and China is in fact moving in the opposite direction: creating more nuclear weapons. If the US and Russia's stockpiles will remain on the same level, many nations will conclude that the weapon states' promise to reduce and eventually eliminate these arsenals has been broken. NNWS may therefore feel released from their pledge not to acquire nuclear arms.

Additionally, there appears to be growing acceptance of the nuclear status of India and Pakistan, with each country acquiring prestige and increased attention from leading nuclear weapon states, including the United States. There is an argument that a nuclear Iran or North Korea could also be absorbed into the international system without serious consequence. If the number of states having nuclear weapons increases, NWS fail to comply with their original disarmament obligations, and countries like India and Pakistan gain status for having nuclear weapons, it is possible that major non-nuclear nations will reconsider their nuclear choices. Most nations will continue to eschew nuclear weapons for technological and economic reasons, but others might decide that nuclear weapons are necessary to improve their security or status. There is a real possibility, under these conditions, of a systemwide collapse of the nonproliferation regime [12].

The NPT has already been severely threatened by the development in several states of facilities for enriching uranium and reprocessing plutonium. Although each state has asserted these facilities for civilian use only, the resulting supplies of nuclear materials give each country a “virtual” nuclear weapon capability. This situation greatly erodes the confidence that states can have in a neighbor’s non-nuclear pledge.

During the last 15 years a new kind of challenge to the nonproliferation regime appeared: countries with clandestine nuclear weapon production programs. One of the first cases of a covert program was revealed in Iraq during the first Gulf War. It was the first discovery of a broad-scale program in a country which was a signatory of the NPT. Iraq (and the later cases of the DPRK, Libya and Iran) proved that the existing safeguards regime is not always effective (especially for detection of undeclared nuclear activities). One of the main reasons for safeguards regime failures is limited resources of the IAEA. The Agency is experiencing the lack of both human and financial assets. For example, the total budget of the IAEA for the year 2005 was 268.7 million dollars, and almost 38% of it was spent on nuclear verification work. It is important to point out that the majority of this money is spent on monitoring large nuclear installations in countries that are not likely to pursue a nuclear weapon capability such as Japan, Canada and major European countries. Very small amounts are left for searching for undeclared facilities and clandestine activities. As an example of the lack of human resources, the creation of an operational unit with limited imagery analysis capabilities [the Satellite

Imagery Analysis Laboratory (SIAL)] can be mentioned. The unit was established in 2000 and as of right now there are two image analysts, one geospatial database administrator and one general staff support person in place in the SIAL [25], which is clearly not enough for full-scale monitoring for illegal nuclear activities throughout the world.

Another major issue of concern is that as time goes by it may become harder and harder to find common points between NPT parties and reach agreements on various problems. In May of 2005, the NPT Review Conference took place in New York. "Delegates from 153 countries failed to build on past agreements and adopt any kind of decision or recommendations for further progress in the vital security issues of nuclear nonproliferation and disarmament. From start to finish, this conference did little more than go through the motions, and was one the most shameful exhibitions of cynical time-wasting seen outside the Geneva Conference on Disarmament" [26]. This conference did not bring any relief of hope for the future development of the nonproliferation regime. Representatives of NPT member states spent most of the time arguing about the agenda and by the time some sort of agreement was reached the conference was over.

These facts indicate that the nonproliferation regime is strained and there is a need for some new ideas and new forces. The number of countries that decide to choose the route of obtaining nuclear weapons for the improvement of their regional and international position is growing. They use the inability of the IAEA to present credible proofs of their violations and complicated mechanisms of reaching the decision to apply UN sanctions against them. Sometimes when information on clandestine programs is coming from intelligence services of one of the member's government, many argue that this evidence was provided for the benefit of the country disclosing information. The IAEA is performing well on monitoring of currently declared facilities, but does not have sufficient resources to keep up with the growing number of illegal weapon programs and discovering them in a timely manner. As the result of those difficulties and disagreements between member states, the popularity of the Agency and trust in the future of the NPT are declining. In this situation, a new independent international organization that can provide sufficient resources and help to the IAEA and nuclear nonproliferation regime as a whole seems to be one of the solutions for the improvement and future development of NPT and gives a hope for a safer future.

# CHAPTER II

# INMAC CONCEPT

## II.A. Introduction

Good verification aims at early detection, to provide sufficient warning of a potential or actual violation, so that other parties can take action before the violation becomes militarily significant [27]. As one way of improving the nonproliferation regime, an additional organization to aid in providing NPT verification is proposed: the International Nonproliferation Monitoring Academic Community (INMAC). INMAC would be a society of academics including students, faculty and staff from both Nuclear-Weapon States and Non-Nuclear Weapon States. In addition to all existing monitoring means, an academic community will provide mechanism of monitoring for proliferation activities. It will help in early detection and building a picture of the scale of undeclared weapons programs. Since INMAC is composed solely of members of the academic community, this organization demonstrates less bias in its investigations or reporting. This community would also provide means for educating the future generation of nonproliferation leaders throughout the world and increased manpower for monitoring for proliferation activities.

## II.B. Nonproliferation Academic Institutions and Nongovernmental Organizations

There are several existing nonproliferation private nongovernmental and academic organizations around the world. Among the major ones are: the Center for

Non-Proliferation Studies (Monterey Institute of International Studies, US), the Global Security Programme (Cambridge University, UK), Bochum Verification Project (Institut fuer Experimentalphysik III, Germany), and the Jaffee Center for Strategic Studies (Israel). Most of these organizations are research centers specializing in arms controls or international security issues. Usually they are small and even being nongovernmental they are still centered on issues related to the host-country.

There are also several professional international communities that are dedicating their resources to aid the IAEA. Among these networks are: International Network of Engineers and Scientists Against Proliferation (INESAP) [28], Independent Group of Scientific Experts (iGSE) on the detection of clandestine nuclear-weapon-usable material production [29], and International Panel on Fissile Materials (IPFM) [30]. These organizations consist of professional engineers and scientists. The main goal of these networks is research and development of innovative monitoring and verification methods. For example, iGSE "has been formed to develop and demonstrate technologies and procedures for remote environmental sampling for clandestine nuclear-weapon-usable materials production and other novel methodologies" [29].

INMAC, on the other hand, would be created as an international community of academics from all over the world, providing resources for open-source verification activities, ways of communication, exchange of ideas and findings, and co-operation in research. The community of academics will be more technical-based than policy-based and will also provide a framework for verification of nonproliferation monitoring results of small research groups within the community. One of the goals of INMAC is to help existing organizations link together and form a backbone for the future community.

## II.C. Available Sources of Information

All unclassified, publicly and commercially available sources of information and data analysis are proposed to be used by INMAC for the detection of undeclared illegal activities intended for the acquisition of fissile materials for nuclear weapons. Among available sources of information and data analysis, the most significant are: commercial satellite imagery systems, commercial computer codes for satellite imagery analysis, Comprehensive Test Ban Treaty (CTBT) verification International Monitoring System (IMS), publicly available information such as watchdog groups and press reports, and custom services information. Combinations of analyzed information obtained from those sources can create a picture of a country's intentions and the scale of its weapons program.

### *II.C.1. Commercial Satellite Imagery*

The use of data acquired by commercial satellites for the verification of the NPT was suggested as early as 1987. Furthermore, the usefulness of multispectral and radar image data for the determination of the operating status of nuclear installations was also demonstrated in 1998. Information gathered from space played an important role in uncovering the nuclear activities of, for example, Iraq, Iran and North Korea. The non-intrusive nature of observations from space adds to its attractiveness [25].

Since the launch of the first civil remote sensing satellite (Landsat 1) by the USA in 1972, the quality of images, measured in terms of the resolution of a sensor, from subsequent civil satellites has improved some 100 fold [25]. There are more than 30 programs in 9 countries existing today: USA, Russia, France, India, Israel, Japan, Canada, and Brazil/China. Currently, there is a variety of different types of remote sensing data available commercially including panchromatic, multispectral, hyperspectral, infrared, thermal and radar imagery. For panchromatic imagery, available spatial resolution is up to 0.6 meters. Prices of satellite imagery greatly vary depending on the type of imagery and the owner of the sensor. The cost of the 0.6 meter resolution data starts from \$18 per $km^2$. Most of the companies have special educational discount programs. Table I shows some of the current and future commercial satellite systems.

TABLE I

Some Current and Future Commercial Remote Sensing Programs Belonging to Different Countries

| Country Satellite | Date of launch of first satellite | Resolution in pixel size (m) | | |
|---|---|---|---|---|
| | | Panchromatic | Multispectral | Thermal/IR |
| **OPTICAL** | | | | |
| *Brazil/China* | | | | |
| Zi Yuan CBERS I & II | 1999-2001 | 20 | 80 | 160 |
| CBERS III & IV | - | 5 | 20 | 40-80 |
| *France* | | | | |
| SPOT-4 | 1998 | 10 | 20 | |
| SPOT-5 | 2002 | 2.5 | 10 | |
| *India* | | | | |
| IRS-1C,-1D | 1995, 1997 | 5.8 | 23.5 | 70.5 |
| IRS-P5 | 1999-2000 | 2.5 | | |
| *Israel* | | | | |
| Eros-A | 2000 | 2 | | |
| *Japan* | | | | |
| ALOS | 2003 | 2.5 | 10 | |
| *Russia* | | | | |
| Resurs-F series | 1989-98 | 2-3, 5-8 | 15-30 | |
| *USA* | | | | |
| KH-1 to 4 | June1959-Dec 63 | 7.6 | | |
| KH-4A | Aug1963-Oct 69 | 2.7 | | |
| KH-4B | Sept1967-May 72 | 1.8 | | |
| KH-6 | March1963-July 63 | 1.8 | 30 | 120 |
| Landsat-5 | 1984 | | 30 (bands 1-5,7) | 120 (band 6) |
| Landsat-7 | 15 April 99 | 15 | 30 (bands 1-5, 7) | 60 (band 6) |
| IKONOS-1 | did not achieve orbit | | | |
| IKONOS -2 | 1999 | 1 | 4 | 4 |
| Quickbird-1 | Failed 2000 | | | |
| Quickbird-2 | 2001 | 0.61 | 2.44-2.88 | |
| Orbview-3 | 2000 | 1-2 | 4 | |
| Orbview-4 | did not achieve orbit | 1-2 | 4 & hyperspectral 8 | |
| Orbview-5 | sch. for early 2007 | 0.41 | 1.64 | |

TABLE I (continued)

| Country Satellite | Date of launch of first satellite | Resolution in pixel size (m) | | |
|---|---|---|---|---|
| | | Panchromatic | Multispectral | Thermal/IR |
| Earlybird-1 | 1997 | 3 | 15 | |
| ASTER | 18 December 99 | | 15 (bands1-3),<br>30m (bands 4-9) | 90 (bands 10-14) |
| EO-1 | 21 November 2000 | 10 | 30 (9 bands)<br>30 (220 bands) | |
| **RADAR** | | | | |
| *ESA*<br>ERS-1, & -2 | 1991 & 1995 | 25 | | |
| *Japan*<br>JERS-1 | 1992 | 18 | | |
| *Canada*<br>Radarsat | 1995 | 8-100 | | |
| *Russia*<br>Almaz-1B | 1998 | 5-7, 15, 30 | 170 | 600 |
| *USA*<br>SIR-C | 1994 | 8-30 | | |

An example of high-resolution satellite imagery is presented in Fig. 5. This is an image of the Uranium Enrichment Plant at Rokkasho (Aomori prefecture, Japan) acquired on June 25, 2002 by the QuickBird sensor owned by DigitalGlobe, Inc. It has 0.6-meter spatial resolution which allows extracting most of the features of the plant including outer and inner fence lines, main entrance gate, main facility buildings, administrative building, storage tanks, switch yard and electric line pole.

Recently a number of online services, offering browsing of high-resolution satellite imagery of the whole globe appeared. Among those services are Google Earth [31], TerraFly [32], TerraServer.com [33] and others. During the last several years the price of this service has been constantly decreasing and now most of those imagery libraries can be accessed for free.

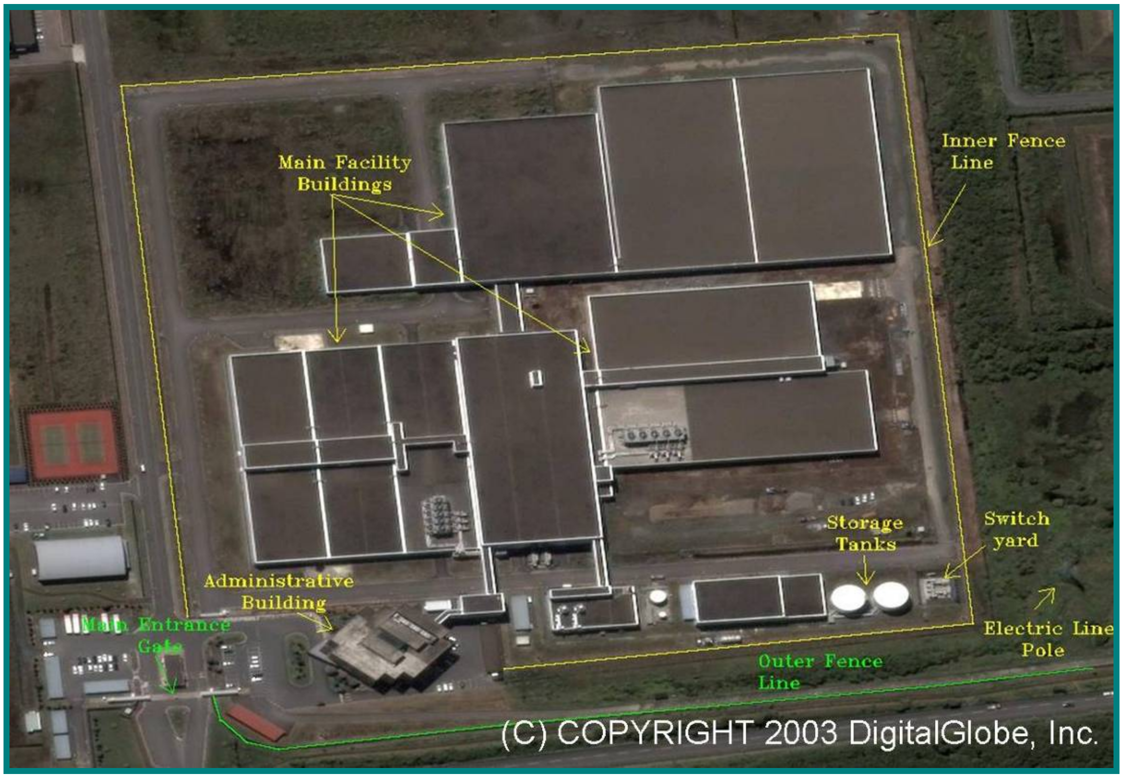



Fig. 5. Uranium Enrichment Plant at Rokkasho Acquired on June 25, 2002 by QuickBird Sensor Owned by DigitalGlobe, Inc.

*II.C.2. Imagery Analysis Computer Codes*

There is a variety of commercially available computer codes for satellite imagery analysis and interpretation, such as ENVI [34], ERDAS [35], SilverEye [36], IDRISI [37] and others. Capabilities of these software tools are improving every day. The most rapidly developing and promising are spectral analysis tools. They allow defining materials of interest and 'mapping' those materials on an image, allowing feature extraction (such as hidden troops). There are also features that allow measuring dimensions of the objects and distances between them, creating 3D models from stereo-pair images and now it is possible to create a 3D surface model (site fly-through) out of a single 2D image. A number of tutorials, books, and training courses for imagery analysis can also be found.

*II.C.3. International Monitoring System*

The International Monitoring System (IMS) is a network of monitoring sensors which search for, detect and provide evidence of possible nuclear explosions to States Parties for verification of Treaty compliance. It consists of 321 monitoring stations and 16 radionuclide laboratories that monitor the Earth for evidence of a nuclear explosion. Raw data from the stations are transmitted to the International Data Centre (IDC). The IDC processes the raw data received from the stations to derive objective products and services which support the treaty verification responsibilities of States [38].

The IMS uses seismic, hydroacoustic and infrasound monitoring technologies to detect the transient signals created when the energy is released in underground, underwater and atmosphere environments, respectively. Radionuclide monitoring technologies collect and analyze air samples for evidence of the physical products created and carried by the winds.

The radionuclide network of 80 stations uses air samplers to detect radioactive particles released from atmospheric explosions or vented from underground and underwater explosions. The relative abundance of different radionuclides in air samples can distinguish between materials produced by a nuclear reactor and a nuclear explosion. IMS radionuclide laboratories analyze samples that are suspected of containing radionuclide materials that may have been produced by a nuclear explosion. Half of the stations in the radionuclide network also have the capacity to detect noble gases. For

INMAC, the presence of noble gases is particularly important in detecting releases from reprocessing plants and reactors. The IMS network has sensitivities on a global scale far better than any radionuclide monitoring system previously available [38].

The verification technologies of the International Monitoring System (IMS) and the data, technologies and products of the International Data Centre (IDC) have the potential to offer a range of useful civil and scientific applications which could contribute to sustainable development and human welfare. These civil and scientific applications demonstrate, in part, how States Signatories could gain additional benefits from participation in the Treaty verification regime. In May 2002, a group of fifteen senior scientific experts gathered in London to identify and examine the potential civil and scientific applications of the Treaty verification technologies [39]. This list includes:

– Worldwide background radioactivity levels
– Historical studies of pollutants and micro-organisms
– Weather forecasting
– Meteorological studies of the dispersion of airborne pollutants and global air mass movements
– Atmospheric tracer studies
– Critical information on nuclear accidents

INMAC could be added to the other applications that could use CTBT data for beneficial purposes.

*II.C.4. Watchdog Groups*

Watchdog groups and groups opposing current regimes inside countries of interest can be a great source of valuable information. For example, Iran's nuclear weapon development program became known to the world with the help of the National Council of Resistance of Iran (NCRI), a group of Iranian exiles opposed to the current regime in their native country. Another organization is Iran of Tomorrow Movement (IOTM). The main goal of this organization is to eliminate the roots of terrorism worldwide, by supporting the people of Iran for the removal of the Islamic Republic in Iran and the establishment of freedom, human rights, and a democratic, secular, and modern government in Iran [40].

Depending on the nature of information provided by watchdog groups it can be used by INMAC for various purposes, for example as a trigger for the initiation of an investigation of a particular country or a particular facility.

*II.C.5. Custom Services Information*

There is an enormous amount of information collected by customs services all over the world. Usually both shipping and receiving countries keep records on all shipments taking place. This information is available and can be helpful for INMAC in building a picture of a country's clandestine nuclear weapons program. The difficulty with using customs services information is that there is a tremendous amount of data. Ways of sorting and extracting useful pieces of data are needed and research in that area would a part of INMAC's mission.

*II.C.6. Other Available Sources*

Among other available sources of information are press reports, the internet, university and public libraries, and various computer codes (air dispersion models, etc.). These sources can provide useful information on a country's profile, various technical data, computational means, etc.

The Internet has changed forever the manner in which individuals might carry out global research. Recent studies have shown that there are over 250,000 databases now available within the "deep web". While the Internet's value is growing, some caution should be used about the source and bias of materials found there. In general, the Internet can provide two benefits to the Academic Community: (1) as a means of rapidly communicating with counterparts around the world, primarily to exchange information and professional insights; and (2) as a means of rapidly accessing both free and commercial information sources [1].

There are numerous commercial online sources, that is, sources that charge either a subscription fee or a usage fee for access to their information. These sources represent decades worth of editorial selection, authentication, formatting, indexing, abstracting, and presentation management. In general, source material obtained through a commercial online premium service has been created by a reputable commercial enterprise subject to scrutiny and judgment of the marketplace. Several examples of such online premium sources are described in Table II [1].

TABLE II

Examples of Commercial Online Premium Sources

| Name | FACTIVA | LEXIS-NEXIS | DIALOG |
|---|---|---|---|
| Link | www.factiva.com | www.lexis-nexis.com | www.dialog.com |
| Description | User-friendly web-based interface, easy means of searching all available publications. Archive of publications varies, but typically provides several years worth of historical file. Includes Jane's Information Group material as well as BBC transcripts. | Two separate channels, one focuses on legal sources including public records (primarily in the United States but very helpful in tracing real estate, aircraft, and water craft including international ships), the other focused on news sources, offering archive access, i.e. ability to reach back several years or more on any topic. | A very large collection of various commercial offerings that can be searched "by the file". Especially valuable for access to conference proceedings, academic and policy journals, dissertations, book reviews, and the Social Science Citation Index (SSCI). |
| Pricing | Flat fee or actual cost pricing. | Flat fee, actual cost, or pay at you go credit card pricing. | Flat fee, actual cost, or pay as you go credit card pricing. |

Grey literature is that information that is both legally and ethically available, but only from specialized channels or through direct local access. It is generally understood as that information whose distribution is not controlled by commercial publishers, and/or that information that is not published, distributed, catalogued or acquired through commercial booksellers and subscription agencies. Grey literature includes working papers, pre-prints, technical reports and technical standards documents, dissertations, data sets, etc. Producers of grey literature include: non-profit and educational organizations, commercial enterprises creating documents for internal use as well as for clients and suppliers, and a wide variety of informal and formal associations, societies, and clubs [1].

Special Libraries Association (SLA) is a professional association for librarian and information professionals working in organizations, companies, governments, and academic institutions. Examples of special libraries include law libraries, news libraries, corporate libraries, museum libraries, and medical libraries. SLA was founded in 1909 in the United States. It is now an international organization with over 11,000 members in over 80 countries. Members of the SLA typically possess a master's degree in library science, but not necessarily for the purpose of library management. Given the rapid adoption of technologies for selecting, analyzing, managing, storing, and delivering information and knowledge, the average SLA member might be performing a range of services and employing a diverse mix of skills related to, but not exclusive of, library science. Unlike academic librarians or municipal librarians most persons working in a special library (or documentation center) work alone, without colleagues. Their budget is often smaller, their target audience more restricted and their collection much more limited in scope. The association is organized into subject-related divisions, geographic chapters, and special interest caucuses. Association activities include conferences, professional education, networking and advocacy [1].

**II.D. Conclusions**

Open sources of information are playing a more important role in monitoring several weapons elimination and arms control treaties including the NPT. Growing number of available sources, especially in electronic form, level of detail, and expanding global communication technologies, provide an extremely powerful toolkit to the IAEA and various interested research groups. At the same time, the rapidly growing amount of information poses another problem of increasing need in manpower for effective data search and analysis. Traditionally professional analysts associate open source information analysis with a number of challenges [1]:

1. *Scarcity of information*. Sometimes there is little information available on a particular individual, organization, or activity.
2. *Information overload*. Sometimes the vast amount of information available on a particular topic requires advanced analysis techniques and careful selection to concentrate the highest priority, most reliable information.
3. *Language barriers*. The most detailed information is often found in the native language of the country under investigation. Such complications also complicate forming effective information search strategies.
4. *Information analysis*. Collecting, organizing, determining associations, tracking, and drawing conclusions from a wide variety of information types can be a daunting task [1].

The proposed community of academics, which would be composed of a number of researchers, would have several advantages over individuals or a small group of analysts. Collaborative efforts of community members would help to minimize and sometimes even completely eliminate most of the challenges described above:

1. *Scarcity of information*. Having members of the community in different countries around the world expands the amount of information and the number of sources that the community as a whole has access to.

2. *Information overload*. Almost unlimited human resources in the universities and schools around the world would provide enough workforce for sorting out and overcoming the information overload.
3. *Language barriers*. Variety of community members with different origins will provide language capabilities for all widely used languages.
4. *Information analysis*. The size of the community and the variety of expertise of its members would provide necessary resources and mechanisms for effective data analysis and compilation.

INMAC would provide an effective addition to the current nonproliferation regime, however, several impediments exist to the formation of such a community. In following chapters a framework for INMAC is developed which will help to address these impediments. Also, case studies will be developed to demonstrate the viability of tools available for academics to assist in nuclear monitoring

# CHAPTER III

# SATELLITE IMAGERY ANALYSIS

## III.A. Background

Since the 1960s, satellite capabilities had been used by the US and USSR for monitoring each other and the rest of the world. In the 1990s, commercial satellite imagery (panchromatic, multispectral, hyperspectral, infrared, thermal and radar) became available to the general public. During the last decade, commercial satellite imagery quality advanced dramatically and its spatial resolution reached values of 0.4 - 0.6 meters. Satellite imagery already has a long history as a valuable tool for non-intrusive treaty verification and now it is gaining its status as a great resource for use by the IAEA and other international organizations for the purpose of monitoring for nuclear nonproliferation regime violations. This chapter explores current commercially availably remote sensing technologies and the feasibility of use of these capabilities by a community of academics.

## III.B. Overview of Existing Remote Sensing Technologies

Remote sensing is a technology for sampling electromagnetic radiation to acquire and interpret geospatial data from which to extract information about features, objects, and classes on the Earth's land surface, oceans, and atmosphere. Most remote sensing data consist of receiving and measuring reflected and/or emitted radiation from different parts of electromagnetic spectrum. Those parts of the spectrum most commonly sampled are the ultraviolet, visible, reflected infrared, thermal infrared and microwave segments. Depending on a segment of the spectrum utilized there are several remote sensor technologies: panchromatic, multispectral, hyperspectral, thermal infrared, radar.

*Panchromatic* is usually a term describing a type of black-and-white photographic film that is sensitive to all wavelengths of visible light. A panchromatic film therefore produces a realistic image of a scene. For satellite imagery it is a single image taken of all wavelengths within the visible spectrum, though not uniformly [41].

*Multispectral* are usually two or more images taken simultaneously, but each image taken in a different part of the electromagnetic spectrum or, in other words, it is closely related, multiband data that consist of radiation collected over sets of electromagnetic radiation that individually extend over (usually narrow) intervals of countinuous wavelength within some part of the spectrum. Each interval makes up a band or channel identified by a color (if in the visible), a descriptive label (e.g. Near IR), or a specified range of wavelengths. Usually multispectral images have around 4-7 bands [41].

*Hyperspectral* is simultaneous acquisition of images of the same area in many (usually 100 or more), narrow, contiguous, spectral bands. The preferred term is “imaging spectroscopy” [41].

*Radar* imagery technology is based on the detection of the amplitude of microwave electromagnetic pulses that are transmitted from and scattered back to an antenna aboard the spacecraft [41].

There are a few important terms widely used for description of satellite imagery parameters that are necessary to be defined in this text:

- The *spatial resolution* of an imaging system is expressed as the area of the ground represented by one pixel. Spatial resolution is also viewed as the clarity of high frequency detail information available in the image. As the spatial resolution increases the details in an image are clearer.
- The *instantaneous field of view (IFOV)* is the ground area sensed by sensor at a given instant in time. The spatial resolution is dependent on the IFOV. The finer the IFOV is, the higher the spatial resolution.
- The *spectral resolution* of an imaging system is the width within the electromagnetic spectrum that can be sensed by a band in a sensor. The narrower the spectral bandwidth is, the higher the spectral resolution [41].

**III.C. Dedicated Nuclear Facilities and Site Signatures**

Many of the capabilities of commercial satellite imagery can be applied to the monitoring of various international treaties. The quality of modern satellite imagery allows investigating even small details of facilities on the ground. This chapter describes the features and signatures of facilities related to the nuclear fuel cycle that can be used for early detection and determination of the real purpose and capabilities of those facilities.

One of the important ways for international communities to monitor for nuclear proliferation is to identify the undeclared nuclear facilities and sites. Modern observation satellites have an ability to cover the whole globe with regular and frequent visits and produce fine resolution images. Different imagery technologies can provide different types of information about the object: panchromatic sensors allow an analyst to use photo-interpretative techniques to recognize structures and objects by their shape, texture, shadows, orientation and context. Unlike panchromatic, multispectral and hyperspectral systems have lower spatial resolution, but they permit identification of materials or compositions of the surface by their spectral signature or color. Thermal satellite imagery has resolution even lower than multispectral imagery, but it carries useful information about the temperature distribution through the object and is very useful in some applications such as facility operational status determination. The last technology to be mentioned is RADAR[§]-imagery. The main advantage of this technology is its active nature and ability to penetrate through objects (e.g. clouds, ground, etc.) [42].

Nuclear fuel cycle facilities have a number of distinct features and signatures that can be extracted from satellite imagery of different types. The combination of imagery technologies provides the best opportunities for target detection and characterization. Although satellite imagery is a powerful tool, it should be understood that it cannot be expected to be a standalone verification method and information from other sources is often needed to help in detecting a facility, defining facility type, and determining its characteristics. Also, information from other sources can aid in recreation of the history and true intentions of the facility.

[§] RADAR is an acronym for **Ra**dio **D**etection **a**nd **R**anging.

Table III contains a summary of available distinct features and signatures for different nuclear or nuclear related facilities. Usually the type of facility can be determined by the presence of a combination of those signatures [43].

TABLE III

Nuclear Infrastructure Features and Signatures of Dedicated Facilities – Parts of Nuclear Fuel Cycle that are Observable from High-Resolution Commercial Satellite Imagery

| Nuclear Facility Type or Operations | Observable Signatures and Features | Limitations |
|---|---|---|
| Uranium Mining Operations | Piles of ore and tailings; large ore trucks; uranium mill | Hard to distinguish from other mining activities |
| In Situ Leaching of Uranium | Pattern of injection wells and production wells, evaporation ponds | |
| Uranium Conversion Facilities | Presence of canisters onsite | Similar to many chemical plants |
| Gaseous Diffusion Plants | Large-area (roof) process buildings; roof ventilations shafts, cooling towers or nearby rivers or lakes, nearby fossil fuel power plants, large electric switchyards (substations); waste management and disposal facilities; security perimeters, railroads, roads, usually an isolated site. | |
| Gas Centrifuge Plants | Switch yard, security fence, large containers of depleted $UF_6$ | Lower electric and water cooling requirements comparing to other processes |
| EMIS Facilities | Small facilities with incoming high-voltage lines, local transformer stations | |
| Reactors | Reactor containment buildings, security perimeters, cooling towers or natural water bodies (with intake and discharge port), high narrow stack (or its shadow), railroads, roads, an isolate site, absence of coal or large oil storage tanks | |
| Reprocessing Plants | Very high stacks (or its shadows), long “canyon-like” buildings, security perimeters, railroads and roads, large-scale water treatment, heavy lifting equipment, electrical power source, an isolated site | |
| Heavy Water Production Plant | Cascade of exchange column, very high stack, large number of water storage tanks. | Similar to other chemical process plants |

*III.C.1. Uranium from Mining Operations*

Mining operations to extract uranium ore can be conducted be open-pit or by underground mining. Moreover, these operations may be exclusively for the extraction of uranium or they may be in conjunction with copper and gold mining. Signatures related to these operations that would be visible to a satellite include the presence of piles of ore and tailings, large ore trucks and the uranium mill, except in the unlikely case of underground mill. In the case of uranium extraction in conjunction with other mining operations, the copper and gold mines themselves become visible indicators of possible uranium mining. The principal difficulty in this case would not be in seeing the mining operation but, rather, in being able to conclude that the mining was for uranium. However this information can be useful in conjunction with other sources of data. Also satellite imagery can be a cost-effective mean for determining the operational status of uranium mines.

*III.C.2. Uranium by in Situ Leaching*

This form of uranium extraction does not involve the digging of ore and usually consists of a number of well fields and a central processing plant. The process involves the injection of a leaching agent into the ore zone through injection wells and the recovery of the resultant uranium solution through a production well.

High-resolution satellite imagery would be able to detect two important features of this means of uranium extraction. First, there is a common pattern of wells consisting of a grid with four injection wells at the corners and a production well in the center; spacing generally ranges from 15 m to 30 m between the injection wells and the production well. Secondly, evaporation ponds to dispose of wastes are a distinctive feature of the in-situ leaching process. These two features would allow distinctive identification of the in-situ leaching process.

*III.C.3. Other Uranium and Thorium Extraction Methods*

Among other extraction of uranium and thorium methods uranium from phosphate, uranium from seawater, thorium from monazite and thorium from uranium ore can also be mentioned. Most of these methods do not have distinguishing signatures on high-resolution satellite imagery; however, the operational status of the known facilities can be determined and continuously monitored.

*III.C.4. Uranium Conversion*

The presence on site of canisters used for nuclear materials could be a strong indicator of a uranium conversion facility. The primary obstacle to conversion plant identification is the similarity between conversion plants and many chemical plants. Identification would be enhanced if it is known that a conversion facility is collocated with a known facility, such as enrichment plant.

*III.C.5. Gas Centrifuge Enrichment*

A common feature of facilities engaged in uranium enrichment using $UF_6$ feed materials is the depleted uranium produced by the processes. Often the large containers of depleted $UF_6$ are stored in the open on large concrete rafts and would be visible from satellite imagery.

Facilities used in this process would have a few signatures distinguishable by satellite imagery. Although the operation of the plant requires electrical power and water cooling, these requirements are low comparing to some other enrichment processes.

*III.C.6. Gaseous Diffusion Enrichment and Aerodynamic Enrichment*

Two enrichment processes with characteristics of interest from a satellite imagery perspective. The high-power demand of both would likely result in a need for the construction of a power plant in the vicinity. In any event, there will be a number of high-voltage supply lines coming into the facility and a large size switch-yard at the plant. Both processes require cooling water that results in a need for a large number of cooling towers and/or cooling ponds. The heat generated in the operation of these plants could also be detectable by infrared satellite imagery. Another common feature of these two enrichment methods is the need for large buildings to accommodate the many stages used in the process.

*III.C.7. Enrichment of $UCl_4$*

$UCl_4$ is a feed material for Electromagnetic Isotope Separation (EMIS) enrichment, Chemical Exchange enrichment and Ion Exchange enrichment. Of the three processes, EMIS offers the best possibility for the use of satellite imagery. EMIS facilities can be housed in a comparatively small building with a few signatures for detection by satellite imagery. However, an electric power demand of several tens of megawatts is required for even small facilities. High-voltage upcoming power lines with local transformer stations should be observable.

Plant structure for the Ion Exchange enrichment process would be modular. Buildings would be less than 10 m high, built to withstand explosions rather than earthquakes. The plants for both Chemical Exchange and Ion Exchange enrichment would have the appearance of a plant in the chemical industry.

*III.C.8. Fuel Fabrication*

There are no observables that would indicate the value of satellite imagery to the purpose of identification of undeclared fuel fabrication activities. Moreover, significant indicators would be unlikely even during construction of these facilities.

*III.C.9. Reactors*

There are several signatures related to satellite imagery identified for reactors, including containment buildings, and the presence of high-voltage power lines and cooling towers. The absence of coal and large oil storage tanks are also important indicators for identifying nuclear power plants. This category of nuclear activity is the most easily distinguishable from satellite imagery.

*III.C.10. Reprocessing*

A commercial scale reprocessing site has several signatures that would help in the identification process using satellite imagery. These include road and rail access for bringing in the spent fuel; high-capacity water supply; large-scale water treatment; cooling towers; heavy lifting equipment; electrical power source; and a building with a heavy duty overhead crane. The presence of transport canisters at the location is also a possibility. These canisters may be from about 2 m to over 6 m long and weigh from 50-100 tons.

*III.C.11. Heavy Water Production*

The ability to identify heavy water production plants from satellite imagery is dependent upon the type of technology used. For the most common technologies, water-hydrogen sulphide exchange process and the ammonium-hydrogen exchange process, there are indicators, such as tall exchange towers, to assist in the detection. The co-location of fertilizer plants in the case of the ammonium-hydrogen exchange process is a significant indicator. The similarity between heavy water production plants and chemical plants adds to the difficulty of identification.

*III.C.12. Research Centers*

Nuclear research centers in most cases can be identified by the presence of a research reactor using its containment building dome as evidence. Tall “smoke” stacks for the dispersal of off-gases are also common indicators.

*III.C.13. Monitoring Reactor Operational Status Using Thermal/Infrared and Radar Imagery*

The most significant indicator of the operational status of nuclear facilities such as a reactor or and enrichment plant is the heat loss. Heat is mostly discharged into large water bodies such as rivers of lakes or even seas or via cooling towers or naturally from buildings into the environment. Multispectral imagery with the thermal/infrared band enables the detection of such discharged water or heat distribution throughout the building. The use of the thermal band gives some indication on the operational characteristics of, for example, a reactor. If the reactor, for instance, is shut down frequently, it might indicate that plutonium is being produced. This would then trigger further investigations. Such information would also be useful to confirm the operational status of declared closed down or decommissioned facilities.

Certain regions of the Earth suffer from prolonged periods of cloud cover or darkness. Under these circumstances, a radar sensor is very useful because of its ability to penetrate clouds and to observe sites even in darkness. There are three important applications for radar imagery:

1. detection of excess heat discharged through cooling water or cooling towers;
2. use of its ability to detect heights;
3. possible detection of underground activities.

Another possible application is a detection of vehicles and their movement near a facility, particularly those that may occur at night or under cloud cover. Some may use the cover of darkness to move, for example, nuclear fuel by trucks or railway in order to avoid detection by optical satellites. Such movement could be detected using radar interferometry.

Often in analyzing an optical image, it becomes difficult to know what a particular signature represents. It may be due to a building or just a disturbance of the soil. This could be resolved by the second application of radar. With a radar signal, it is possible to measure height very accurately and it is possible to construct a contour map of the site that would assist in determining the nature of the observed signature.

Moreover, power lines are not always easy to detect in an optical image unless there is a good contrast. On the other hand, with radar, pylons carrying power cables and railway lines can be readily observed.

*III.C.14. Google Earth*

Google Inc. is the world's leading company in providing web-search services. The company was created in 1998 and has been rapidly growing ever since. In 2004, Google announced the acquisition of Keyhole Corp., a digital and satellite image mapping company. The acquisition gave Google users a powerful new search tool to view images from satellites across the Earth. The new project was called Google Earth. A small desktop client that connects to the huge online database of satellite images covering the whole globe has been created. Main features of the program are:

- the program is free for personal use,
- sophisticated streaming technologies allow data delivery at the moment when it's needed,
- several terabytes of satellite and aerial data cover all of the Earth,
- high-resolution data are available for multiple cities and places around the world,
- easy-to-use search engines allow fast finding of places of interest.

Google Earth can provide a great tool for browsing the Earth and exploring places of interest. To satisfy the goals of this study, the availability of high-resolution imagery data for nuclear fuel cycle facilities all over the world has been investigated. Detailed images of the nuclear installations of Russia, USA, Japan, China, Iran, North Korea, India, and Pakistan were found and marked. Most of the images are dated from 2005-2006. In Fig. 6 an image of Pakistan's Khushab facility is presented. It is a very clear, high-resolution picture and most of the details of the heavy-water plutonium production reactor, heavy-water production plant and a new reactor construction site can be easily distinguished.


Fig. 6. Khushab Plutonium Production Complex, Pakistan.

Another example is shown in Fig. 7, where Lake Karachai at Mayak PA in Russia is presented. This is one of the most contaminated places on the planet. The lake contains millions of Curies of fission products that were dumped as waste during the early years of the Soviet nuclear weapons program. Now there is an ongoing activity aimed at the elimination of the lake by filling it with dirt and concrete. Results of those activities can be clearly seen on this image.


Fig. 7. Lake Karachai, Mayak PA, Russian Federation.

There are several advantages in Google Earth for INMAC. Availability of the current and detailed imagery proves Google Earth to be a valuable source and search engine for finding nuclear installations and undeclared facilities all over the world and performing visual inspection and initial characterization of those facilities. The "Google Earth Community" is a group of users from all over the world, who browse through the database and mark various places that they find interesting or they have information about. Those locations, sometimes with comments and additional information, are shared among the members of the community. Findings of the members of this community can be a valuable source of information related to undeclared nuclear-related activities.

**III.D. Satellite Imagery Analysis**

Imagery analysis is the last and the most important step in identification of dedicated nuclear facilities. There are several techniques that are used for analysis of different types of imagery. Usually one type of satellite imagery and analysis routine specific to this type of imagery are used. But in order to obtain the best results possible a combination of images and analysis techniques should be used.

For the purpose of this study, investigation of imagery analysis capabilities was performed in the form of a case study. For the case study a 0.6-meter resolution panchromatic and 2.4-meter resolution multispectral images of the Rokkasho area in Japan were chosen. The attractiveness of this region is in the co-location of an operational uranium enrichment plant, low-level radioactive waste disposal site, and a construction site for reprocessing and MOX fuel fabrication facilities. Images were acquired on June 25, 2002 by the QuickBird sensor owned by DigitalGlobe, Inc.

The ENVI® Software package by Research Systems Inc. was used as the main tool for imagery analysis, classification, and annotation. ENVI® (the Environment for Visualizing Images) is an image processing system designed for analysis of satellite and aircraft remote sensing data. The software package provides basic and advanced tools for processing and analyzing panchromatic, multispectral, hyperspectral and radar remote sensing data. Software capabilities include data transforms, filtering, classification, registration and geometric corrections, spectral analysis tools, and radar tools [44].

*III.D.1. Panchromatic Imagery Analysis and Annotation*

When analyzing remote sensing data, the first task is to identify places or regions of interest. One way of doing that is browsing large areas looking for specific signatures or suspicious objects. This method is not very efficient and time/resource consuming. Some specific search system should be defined in order to optimize search process. One of the ways of searching for nuclear installations suggested in this study is utilizing the feature most common to the majority of nuclear fuel cycle related facilities – high electric power consumption. The idea is that tracking electric high-voltage power lines can help finding facilities with high-power consumption and lead to further investigation of the functions of those facilities by comparing them to a library of signatures specific to various facilities of interest.

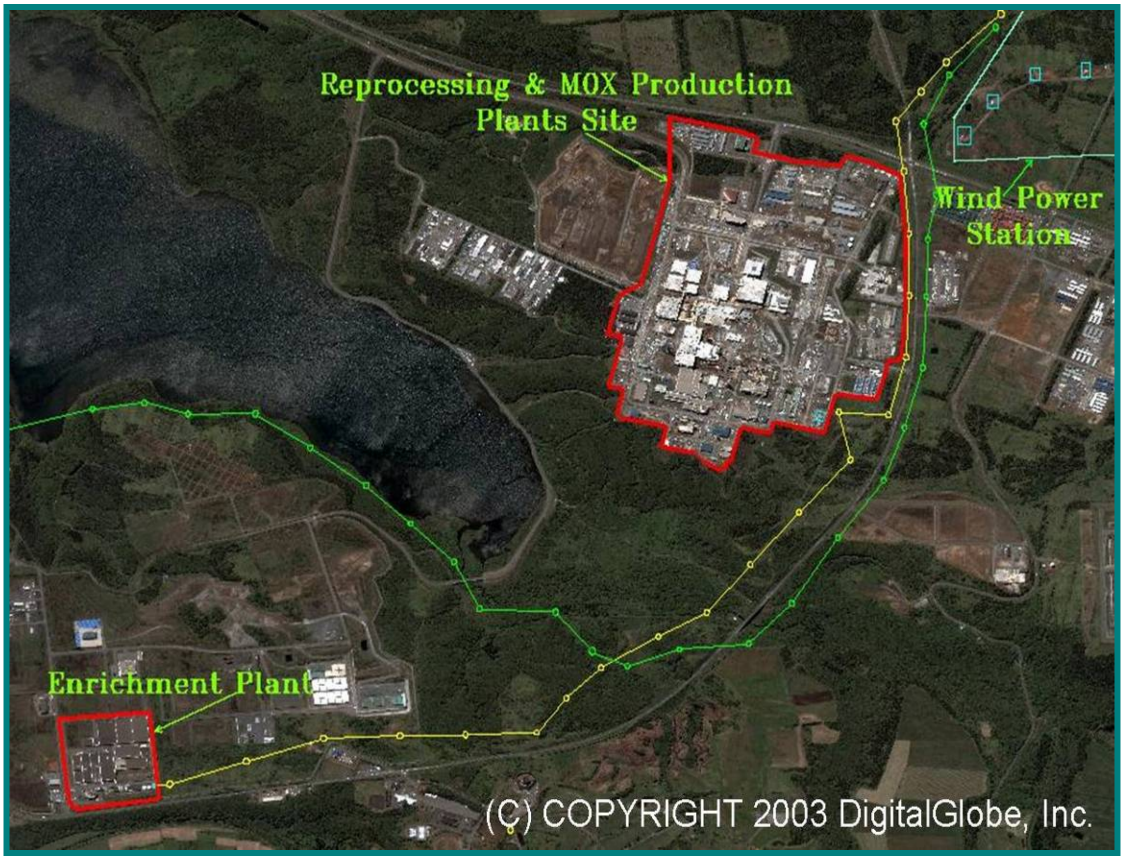



Fig. 8. Tracking the Electric System of the Rokkasho Site.

Analysis results of the electric power distribution system of the Rokkasho site are presented in Fig. 8. By tracing the electric poles, two major power lines were defined. The green line is supplying power to the Rokkasho village, which cannot be seen in this figure. The yellow line is specifically supplying the uranium enrichment plant and reprocessing and MOX fuel production plants. One of the power sources of the Aomori prefecture where Rokkasho is located, a wind power station, was also discovered on the image.

Analysis of this image was performed by step-by-step visual identification of each individual electric pole and marking it. Automation of the process of mapping high-voltage power lines can make searching less time consuming and allow creation of a "power distribution" profile for a country or a region of interest with minimal human operator involvement. Review of the created profile can lead to the discovery of unknown and suspicious facilities.

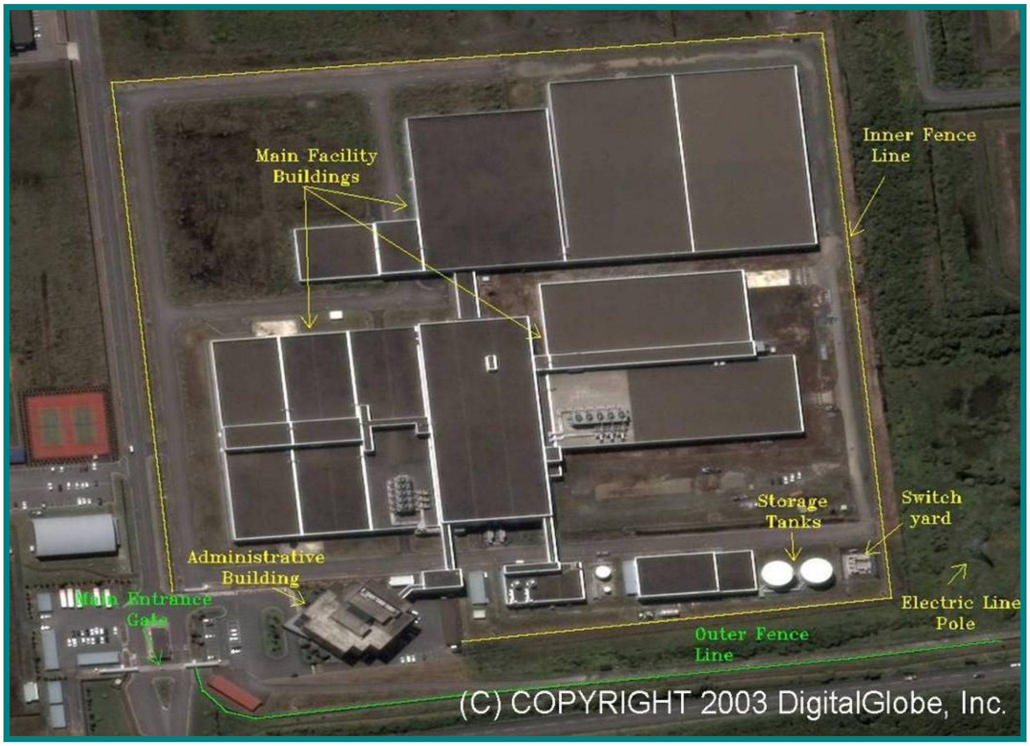



Fig. 9. Uranium Enrichment Plant at Rokkasho, Japan.

After the facility is localized, the next step is to explore its characteristics and annotate them. In Fig. 9, an annotated image of the Uranium Enrichment Plant at Rokkasho is presented. High spatial resolution allows extraction of various features of the plant. Process buildings with large roof areas, double security perimeter (fence), incoming high-voltage electric lines, switch yard and other signatures typical to centrifuge enrichment plants can be easily seen on this image. Several other characteristic features were discovered: main entrance gate, administrative buildings, loading docks, air ventilation systems, etc.

More detailed information about the facility can be extracted from the high-resolution satellite image. For example, modern imagery analysis software allows performing measurements of dimensions of objects on the image. The measurement results of the dimensions for the main centrifuge halls of the Rokkasho Uranium Enrichment plant performed with the help of the ENVI software are presented in Fig. 10.


Fig. 10. Measurement of the Dimensions of the Main Centrifuge Halls of the Rokkasho Enrichment Plant.

Using these data and information found in open literature it became possible to calculate some characteristics of this plant. For a typical centrifuge enrichment facility, enrichment capability is about 20 kg SWU per $m^2$ of the facility [45]. Knowing that, enrichment capabilities of each building and of the whole plant were calculated. This estimated a capacity of 1,037 ton SWU. Results were compared to the official information on the Rokkasho Enrichment plant and appeared to be within 1.2% of the actual capacity of the enrichment plant which is listed as 1,050 ton SWU of separative power [46].

A typical modern centrifuge uranium enrichment plant produces about 4 SWU per centrifuge and utilizes about 200 kWh per SWU. Using these characteristics and plant capacity calculated earlier, the electric power consumption of the plant was estimated at 23.7 MW, and the approximate number of centrifuges in this facility was estimated to be 260,000. The measured data are summarized in Table IV.

TABLE IV

Calculation of Separative Power and Electric Power Consumption of the Rokkasho Enrichment Plant

| Building N | X (m) | Y (m) | Area (m2) | kg SWU/ m2 | kg SWU | SWU/ centri-fuge | N of centri-fuges | kWh/SWU | W |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 32.0 | 126.5 | 4048 | 20 | 80960 | 4 | 20240 | 200 | 1.85E+06 |
| 2 | 33.4 | 126.5 | 4225 | 20 | 84502 | 4 | 21126 | 200 | 1.93E+06 |
| 3 | 33.4 | 126.5 | 4225 | 20 | 84502 | 4 | 21126 | 200 | 1.93E+06 |
| 4 | 52.9 | 126.5 | 6692 | 20 | 133837 | 4 | 33459 | 200 | 3.06E+06 |
| 5 | 120.0 | 50.0 | 6000 | 20 | 120000 | 4 | 30000 | 200 | 2.74E+06 |
| 6 | 98.5 | 45.7 | 4501 | 20 | 90029 | 4 | 22507 | 200 | 2.06E+06 |
| 7 | 38.3 | 32.6 | 1249 | 20 | 24972 | 4 | 6243 | 200 | 5.70E+05 |
| 8 | 21.2 | 32.6 | 691 | 20 | 13822 | 4 | 3456 | 200 | 3.16E+05 |
| 9 | 68.0 | 97.0 | 6596 | 20 | 131920 | 4 | 32980 | 200 | 3.01E+06 |
| 10 | 60.1 | 113.5 | 6821 | 20 | 136427 | 4 | 34107 | 200 | 3.11E+06 |
| 11 | 60.1 | 113.5 | 6821 | 20 | 136427 | 4 | 34107 | 200 | 3.11E+06 |
| **Total:** | | | 51,869 | | 1,037,398 | | 259,349 | | 2.37E+07 |

*III.D.2. Multispectral Imagery Analysis*

Visual analysis of panchromatic imagery can provide a great amount of useful information, but it has certain limitations defined by image spatial resolution and image quality. The purpose of multispectral imagery analysis, performed during this study, was to enhance the results obtained from panchromatic imagery interpretation and to investigate the potential for automation of imagery classification and the use of spectral signatures for tracing various materials and compounds.

**III.D.2.A. Pansharpening**

Usually multispectral imagery has lower spatial resolution than panchromatic imagery; therefore, it has less spatial information. Recently, the technique of *pansharpening* was developed. Pansharpening is a pixel level fusion technique used to increase the spatial resolution of the multispectral image using a panchromatic image of the same area. These techniques allow increasing the resolution while simultaneously preserving the spectral information in the multispectral data. The resulting picture has the resolution of a panchromatic image and retains most of the spectral information from the original multispectral image [47].

An example of a multispectral image before and after pansharpening is presented in Fig. 11. On the left-hand side, most of the features of the regular 2.4-meter multispectral image are not visually recognizable. On the right-hand side the sharpened image, an observer can make a conclusion about the presence of a high stack and surrounding infrastructure.

Fig. 11. Example of a Multispectral Image Before and After Pansharpening.

A multispectral image with higher spatial resolution may provide feature enhancement, increased classification accuracy, and help in the detection of various materials or changes on site. There is a set of sharpening algorithms available in ENVI Imagery Analysis software. Among them are: HSV (hue, saturation, value) transform, color normalized (Brovey), Gram-Schmidt spectral sharpening, PC (principal component) Spectral Sharpening, and CN (color normalized) Spectral Sharpening. For each of the sharpening routines a number of resampling techniques (Nearest Neighbor, Bilinear and Cubic Convolution) is available [44].

### III.D.2.B. Multispectral Imagery Classification

Multispectral sensor technology performs subdivision of spectral ranges of radiation into bands (intervals of continuous wavelengths), allowing sensors in several bands to form multispectral images. For any given material, the amount of solar radiation that reflects, absorbs, or transmits varies with the wavelength. This important property of matter makes it possible to identify different substances or classes and separate them by their *spectral signatures* (spectral curves), as shown in Fig. 12.

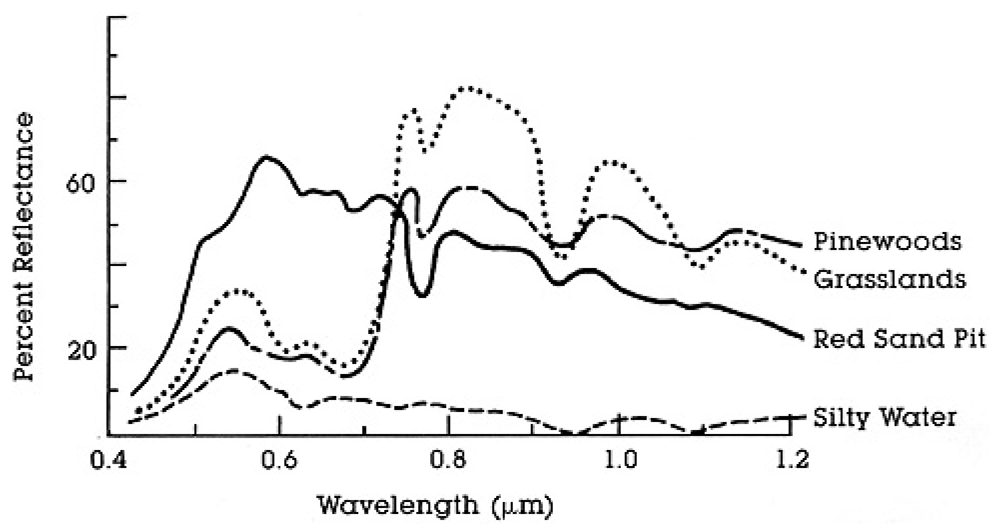



Fig. 12. Percent Reflectance of Light for Different Materials [41].

For example, at some wavelengths, sand reflects more energy than green vegetation but at other wavelengths it absorbs more (reflects less) than does the vegetation. In principle, it is possible to recognize various kinds of surface materials and distinguish them from each other by these differences in reflectance.

This principle was used to map various classes of materials on a multispectral image of the Rokkasho site. In the ENVI Imagery analysis software there are several different algorithms available to perform spectral signature extraction and classification using those signatures. Routines are separated in 2 groups: unsupervised and supervised. For unsupervised classification, features are separated solely on their spectral properties without any input from the operator. Supervised classification algorithms use some prior or acquired knowledge of the classes in a scene. The operator is setting up training sites or regions of interest (ROI) to estimate and identify the spectral characteristics of each class. Multispectral imagery classification algorithms available in ENVI are listed in Table V.

TABLE V

Multispectral Imagery Classification Algorithms Available in ENVI Software Package

| **Unsupervised** | **Supervised** |
|---|---|
| IsoData<br>K-Means | Parallelepiped<br>Minimum distance<br>Mahalanobis Distance<br>Maximum Likelyhood<br>Spectral Angle Mapper<br>Binary Encoding<br>Neural Net |

Different combinations of sharpening and classification algorithms can produce results of different quality for imagery from different sensors. Moreover performance of the same sensor may vary for different areas on Earth. For each sensor type, there is a set of sharpening and classification routines that are capable of producing the best possible results. There are 112 possible combinations of available sharpening and classification algorithms in ENVI. An investigation of all available combinations of routines was conducted.

In order to organize and structure output data, the naming convention presented in Table VI was created. Some of the parameters required two letters in the file name because of several additional options within them.

A few initial tests were conducted to compare the performance of unsupervised and supervised classification algorithms. The quality of the results produced by unsupervised routines was not suitable for the purpose of this project. A decision was made to use supervised algorithms only.

TABLE VI

Imagery Classification Output File Naming Convention

| Letter | Parameter | Values |
|---|---|---|
| 1st | Scene | F – Full Scene<br>E – Enrichment Plant<br>R – Reprocessing Plant<br>M – MOX Fuel Fabrication Facility<br>L – LLW Lanfill |
| 2nd | Sharpening Algorithm | H – HSV<br>G – Gramm-Schmidt<br>P – PC Spectral<br>C – CN Spectral |
| 3rd&4th | Resampling Technique | NO – Nearest Neighbor<br>BO – Bilinear<br>CO – Cubic Convolution<br>NA – Nearest Neighbor + Average<br>NS – Nearest Neighbor + Sensor<br>BA – Bilinear + Average<br>BS – Bilinear + Sensor<br>CA – Cubic Convolution + Average<br>CS – Cubic Convolution + Sensor |
| 5th | Classification Method | P – Parallelepiped<br>M – Minimum Distance<br>D – Mahalanobis Distance<br>L – Maximum Likelihood<br>S – Spectral Angle Mapper<br>B – Binary Encoding<br>N – Neural Net |
| 6th | Reserved for Parameter Variation in Classification Methods | O – Default Parameters |
| 7th&8th | Reserved | 00 – Default |

In order to define a combination that can provide the best possible classification results a two-step benchmark study was planned. The first step included analysis of a full scene multispectral image using all possible combinations of the sharpening and classification routines. This step was intended to outline a set of sharpening and classification algorithms combinations that provide the best results for QuickBird multispectral imagery. During the second step, the chosen set of algorithms was used for thorough analysis of smaller parts of the image that included only one of the nuclear facilities.

### III.D.2.C. Full Scene Image Classification

For the full scene image classification, eight basic classes of materials were selected and colored Regions of Interest (ROI) were specified. The color codes and associated color names used in ENVI are listed in the

Table VII. Several types of materials were chosen for classification of the full scene image. The fist type was for substances most common in the image, such as healthy vegetation and open water. The second type was for materials widespread on facility sites and construction areas: pavement, dirt and several kinds of roof material and metal constructions. One of the intentions was to also prove that this technique can be used for automatically allocating various features such as electric power line system.

TABLE VII

Classes and Color Codes, Defined for Full Scene Image Classification Analysis

| Class Description | ENVI Color Name | One Letter Code | Color Reference |
|---|---|---|---|
| Metal Constructions | Red | M | |
| Healthy Vegetation | Green 3 | V | |
| Open Water | Blue | W | |
| Pavement | Green | P | |
| Dirt | Yellow | D | |
| “Grey” Roof Material | Cyan | G | |
| Storage Tank Roof Material | Magenta | T | |
| Lab Building Roof Material | Purple | L | |

The full scope of pansharpening and image classification analysis was performed after classification classes were selected and defined. As a result of this analysis, 336 files (112 images) occupying about 100 Gb of memory space were created. After visual analysis of all images, the 10 most suitable combinations of sharpening and classification techniques were selected. It appeared that not all of the combinations performed uniformly with different classes. Several correlations between sharpening and classification algorithms performance with different classes were discovered. It is recommended that a set of different routines combined with classes which they perform best should be used. Resulting combinations of algorithms and groups of classes that are capable of producing suitable results are presented in Table VIII. The last column of the table shows sets of classes of materials for which selected algorithms work best.

Only the Gramm-Schmidt sharpening algorithm performed well enough for the Quickbird sensor imagery to produce images suitable for classification. Other techniques did not provide satisfactory results and were not used in future analyses.

TABLE VIII

Combinations of Sharpening and Classification Techniques and Associated Classes Suitable for Full Scene Image Analysis

| Sharpening Algorythm | Resampling Technique | Classification Method | Best Fit Classes |
|---|---|---|---|
| Gramm-Schmidt | Bilinear + Average | Binary Encoding | V, W |
| | | Maximum Likelihood | V, W, D |
| | | Parallelepiped | V, W, D, M, L |
| | | Spectral Angle Mapper | V, W |
| | Bilinear + Sensor | Parallelepiped | V, W, D, M, L |
| | | Spectral Angle Mapper | V, W, M, L, G |
| | Cubic Convolution + Average | Parallelepiped | V, W, M |
| | | Spectral Angle Mapper | V, W, M, L, G |
| | Cubic Convolution + Sensor | Parallelepiped | V, W, M, S |
| | | Spectral Angle Mapper | V, W, M, L, G |

All selected combinations performed well with vegetation and water. This observation can be explained by the fact that spectral signatures of those classes are easily distinguishable from others, and also that these two classes are the most abundant in the image. Another observation was that none of those combinations were suitable for all defined classes at the same time. The most number of classes that each of these combinations of routines was fitting well was five. Also, it appeared that there were no good results produced for pavement classes. The explanation for this effect is in the selected ROI that was not fully representative of all pavement areas on the image.

Examples of images resulting from sharpening and classification are presented in Figs. 13 and 14. Figure 13 is an image created using the Gramm-Schmidt sharpening with Cubic Convolution plus Average of Low Resolution Multispectral File resampling technique and Spectral Angle Mapper classification.

Fig. 13. Full Scene: Gramm-Schmidt Sharpening, Spectral Angle Mapper Classification.

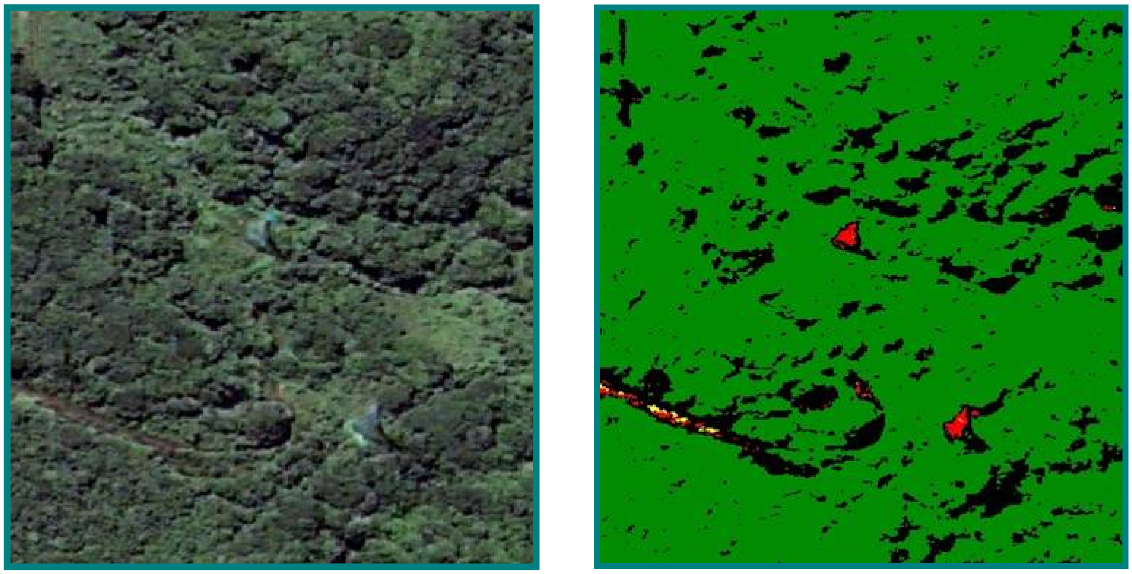


Fig. 14. Visual Localization of Electric Poles in the Forest: Unclassified Image (Left) vs. Classified (Right).

In Fig. 14, fragments of unclassified and classified images showing two electric poles, located in the forest, are presented. Poles cannot be easily distinguished visually on the unclassified image. The classified image shows them clearly marked as metal constructions. All classified images that were selected as suitable for future analysis can be found in Appendix A.

**III.D.2.D. Reprocessing Plant Image Classification**

The first step of multispectral imagery analysis revealed a number of sharpening and classification routines suitable for Quickbird sensor imagery analysis. The second step was intended to expand the level of detail of analysis by applying chosen algorithms to a smaller area of the scene. A part of the image containing the Rokkasho Reprocessing Plant construction site was chosen. Using ENVI's "shape file" capability which allows extraction of the same geo-referenced areas from the images with different spatial resolution, new multispectral and panchromatic images were created. New images were then used as feed data for sharpening routines of the ENVI software.

Because this part of the study was intended to provide more details about the composition of the area, new materials were selected for classification of reprocessing plant construction site. Two grades (dark and light) of dirt and vegetation were selected. Then a set of specific construction materials was selected: “grey” and “blue” roof materials, metal constructions, pavement, “yellow” piping connecting buildings, water cooling units and “blue” isolating material for underground structures. All defined classes and associated color codes are presented in Table IX.

TABLE IX

Defined Classes and Color Codes for Reprocessing Plant Construction Site Analysis

| **Class Description** | **ENVI Color Name** | **Two Letter Code** | **Color Reference** |
|---|---|---|---|
| Dark Dirt | Red | DD | |
| Light Dirt | Maroon | LD | |
| Dark Vegetation | Green 3 | DV | |
| Light Vegetation | Green | LV | |
| “Golden” Piping | Yellow | GP | |
| “Grey” Roof Material | Cyan | GR | |
| “White” Roof Material | Magenta | WR | |
| Blue Roof Material | Blue3 | BR | |
| Metal Constructions | Blue | MC | |
| Pavement | Sienna | PV | |
| Cooling Water Sub-facility | Purple3 | CW | |
| “Blue” Underground Structures | Thistle1 | US | |

All sharpening and classification routines selected during the full scene imagery analysis and a few additional routines were applied to the reprocessing plant construction site image. During the analyses, 36 images were created, 3 images appeared to be suitable for analysis. Appropriate algorithms are summarized in Table X. One of the main improvements comparing to the full scene analyses was in the fact that the selected three sets of algorithms provided suitable results for all classes of materials at the same time.

TABLE X

Combinations of Sharpening and Classification Techniques and Associated Classes Most Suitable for Reprocessing Plant Construction Site Image Analysis

| Sharpening Algorythm | Resampling Technique | Classification Method | Best Fit Classes |
|---|---|---|---|
| Gramm-Schmidt | Bilinear + Average | Mahalanobis Distance | All |
| Gramm-Schmidt | Cubic Convolution + Average | Mahalanobis Distance | All |
| Gramm-Schmidt | Cubic Convolution + Sensor | Mahalanobis Distance | All |

In Fig. 15, a full classified image of the reprocessing plant construction site is shown. As can be seen in the image, most of the areas of interest were detected and mapped appropriately by the analysis routines. Similar to the full-scene analyses, mapping algorithms provided the best performance on the materials that are the most abundant in the image, such as vegetation, dirt, and paving. Most of the roof and piping connecting buildings materials were also detected correctly. Metal constructions, such as electric poles allowed defining the electricity supply lines. In case of cooling water sub-facilities:  facility, where the initial ROI was chosen, was mapped completely with the right color. The second water cooling facility was not completely identified, although parts of it were mapped with the right color which can provide an idea to an operator about the purpose of the whole facility.

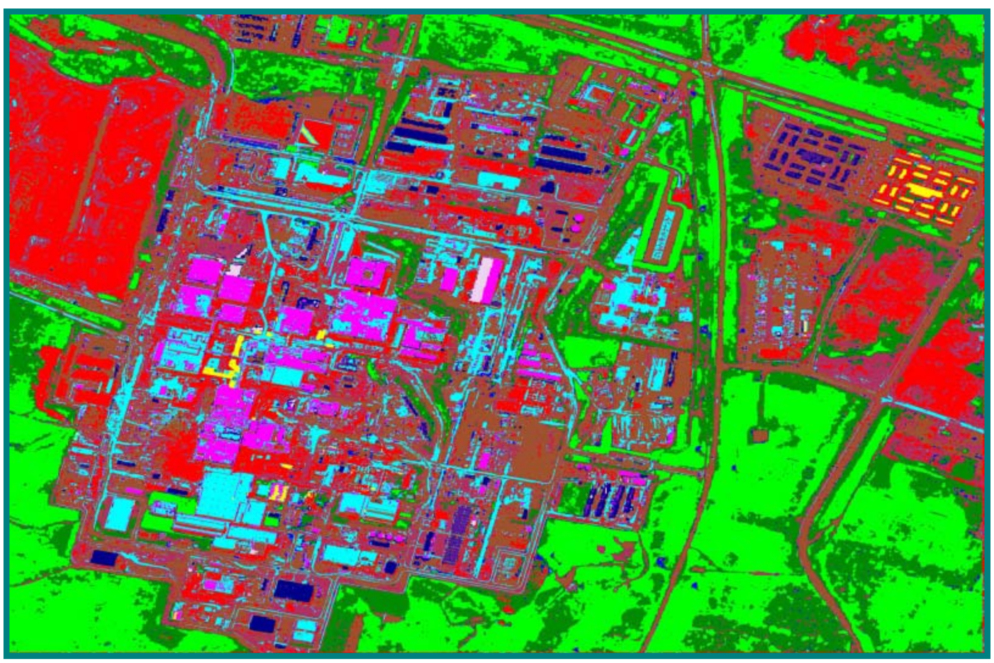


Fig. 15. Classified Image of the Reprocessing Plant Construction Site.

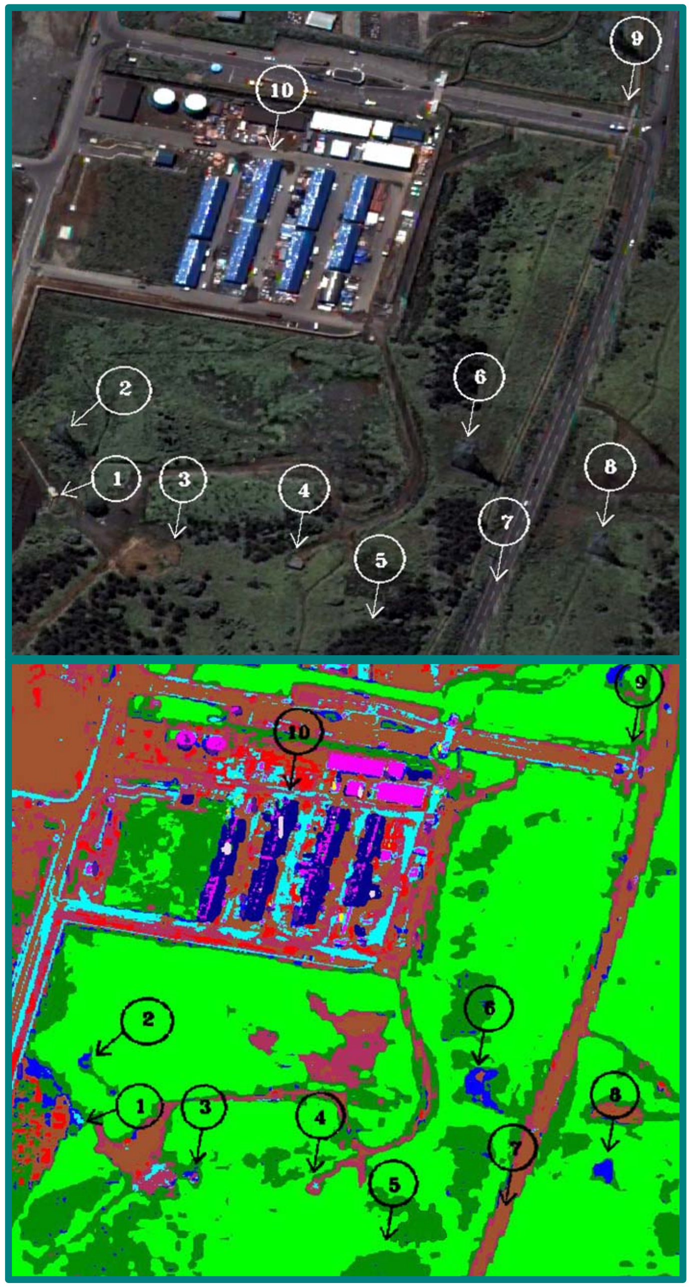



Fig. 16. Comparison of Multispectral and Classified Images of the Reprocessing Plant Construction Site.

In Fig. 16 fragments of sharpened and classified images are presented. This figure provides more detailed information about the performance of the sharpening and mapping routines. Some of the prominent findings are highlighted on the images and described below:

1. Numbers 1 and 4 are two small buildings outside the main facility fence that were not easily noticeable on the regular multispectral image. Buildings were detected and marked as “grey” roof material on the classified image. This is an important example of locating “hidden” or camouflaged buildings that could possibly be missed during the visual inspection of the area image. In case of unknown facility this ability will allow to find covert buildings, for example, antiaircraft guns protecting covert facility from air strikes.
2. Numbers 2, 6 and 8 are electric powerline poles in the forest. These poles were successfully detected and marked. This example demonstrates an ability to trace electric powergrid of the area and identifying facilities that are high electric power consumers.
3. Number 3 shows successful detection and mapping of dirt patches in the forest. This demonstrates an ability of classification algorithms to distinguish between several similar classes of material and properly map them.
4. Similar to number 3, number 5 demonstrates classification algorithm capabilities.
5. Number 7 shows successful mapping of paving and asphalt. During the full scene analysis paving was often detected as dirt or as one of the

roof materials. The problem was in the similarity of spectral signatures of the ROIs chosen for those materials. After some tuning and choosing a different ROI for paving it was effectively separated and mapped.

6. Number 9 shows facility entrance gate.
7. Number 10 - “blue” building roofs.

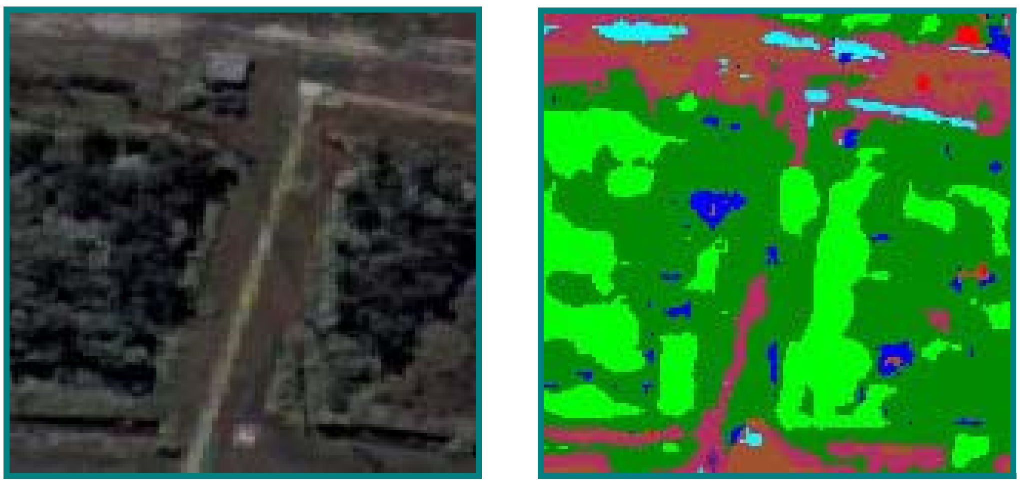


Fig. 17. Example of Erroneous Detection and Mapping of Several Areas on the Image.

Together with multiple successes in classification of important areas of interest, there were also some examples of mistaken or incorrect detection of some areas and materials. For example in Fig. 17 an erroneous detection of several metal constructions (electric pole) in the forest area is shown. Those small areas in the forest appeared to be darker and their spectral signatures are close to the signature of metal constructions. Several more misinterpretations can be found in this figure such as dirt areas mapped as vegetation and a small square building in upper part of the image mapped as paving. Among the main reasons for those misinterpretations are:

- lack of spectral information (low spectral resolution): multispectral images have only 4 bands. Often spectral signatures for several materials are very, an image with higher spectral resolution is needed to resolve those materials.
- image nonuniformity: spectral characteristics of the same materials may vary throughout an image, because of variation in their composition, amount of reflected light, presence of mixtures of several materials, etc.

**III.E. Satellite Imagery Analysis Conclusions**

In this chapter it was proven that panchromatic and multispectral imagery analyses are two powerful and valuable tools for monitoring of illegal nuclear proliferation activities. Panchromatic imagery available on the market provides superior spatial resolution of up to 0.6 meters per pixel. It can be used for visual investigation of the areas of interest and for the quest for signatures specific to nuclear fuel cycle facilities. Multispectral imagery on the other hand has lower spatial resolution compared to panchromatic imagery. With the help of the new sharpening techniques it is possible to create good quality high-resolution multispectral images with the resolution of panchromatic image and preserving the level of detail of spectral information. Several classification routines are available for detailed material mapping and analysis of sharpened images. During this study two images were analyzed: Rokkasho site full scene and Rokkasho reprocessing plant construction site. The ENVI imagery analyzing software package was used for all analyses. In both cases several sets of sharpening and classification techniques that provided the best results for the Quickbird sensor multispectral imagery were defined. Use of these routines allowed successful classification and mapping of various materials present in those scenes. It was proven that multispectral imagery analysis together with high-resolution true-color imagery analysis can be a very valuable tool for tasks like locating “hidden” or camouflaged buildings or troops, automatic mapping of scene’s power gridlines, defining sources and recipients of electric power, and other tasks involving classification of various materials and determination of functions of facilities of interest. Overall performance of analysis routines was satisfactory. Most of the materials and areas under investigation were properly detected and mapped by the software. Also some mixed and erroneous results were produced for several types of materials. Most of those misinterpretations can be explained by the lack of spectral resolution in multispectral imagery. Several of those discrepancies were successfully corrected by “fine tuning” (better choice of ROI’s specific to materials, use of different algorithms, and variation of parameter of analysis routines).

Proof of applicability of satellite imagery analysis for tracking nuclear nonproliferation regime violations suggests it as one of the main search and investigation tools for INMAC. Satellite imagery can aid in a wide variety of tasks starting with locating suspicious facilities and all the way to determining detailed characteristics of particular facilities and sites. When this imagery analyses is extensively utilized by INMAC, a database of best sets routines and associated parameters for different types of imagery, various sensors, terrains, etc. is proposed. This type of database would help to avoid time consuming preliminary analysis and would allow quick and high quality results. Time is very important parameter in detection of covert nuclear weapons program and revealing it to the world. Also development of automated software that is capable of recognizing imagery types and applying appropriate analysis routines is proposed. Special thresholds can be set up for presence of specific materials and some other criteria based on which the software will warn an operator about the presence of suspicious objects. Human operator analysis can be used on the areas specified by the software in order to create final conclusions.

# CHAPTER IV

# BLIND TEST CASE SATELLITE IMAGERY ANALYSIS

## IV.A. Problem Statement

As a part of this research project investigation of satellite image of an unknown nuclear facility was performed. The goal of this task was to determine the type of the nuclear facility using visual signatures specific to nuclear installations without any prior knowledge about the facility. Unknown case was provided by professor Charlton as a bundles multispectral (4 bands, 2.4-meter resolution) and panchromatic (1 band, 0.6-meter resolution) acquired by the QuickBird sensor. Imagery analysis should result in description of a set of features of the facility on the image, which are also specific to various nuclear fuel cycle facilities. Based on these signatures, the type(s) of the facility(ies) on the image should be determined. Obtained results will be compared with the existing known information about installations.

## IV.B. Preliminary Analysis Steps

For effective visual analysis a natural color high-resolution image is desired. The first step in analysis of an unknown nuclear facility image was pan-sharpening of an existing low-resolution multispectral image. Based on the experience obtained during the known imagery analysis described in Chapter III, a Gramm-Schmidt sharpening routine was chosen together with the Nearest Neighbor resampling technique. As a result a multispectral image with the resolution of 0.6 meters was created and saved. High resolution multispectral was than converted into a natural color composite image. All visual analyses were performed on the natural color image.

*IV.B.1. Full Site Description*

The site on the image is a group of co-located facilities. During the initial inspection of the site security fence lines were annotated. The result was a set of eight separately fences areas and a large fence surrounding the full site (light green line). The full scene image with annotated fenced areas is presented in Fig. 18.

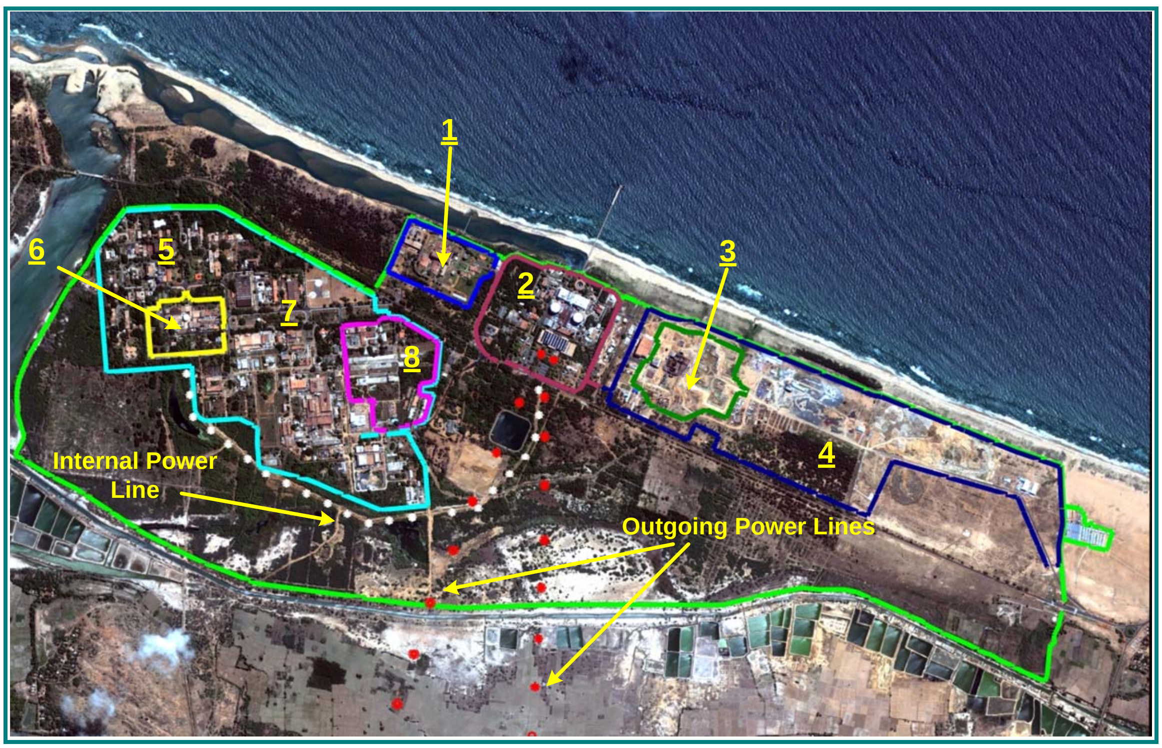



Fig. 18. Full Scene Visual Analysis Results.

Visual analysis of the site revealed the presence of several suspected nuclear fuel cycle facilities on this site, including nuclear reactors, nuclear fuel reprocessing plant, waste treatment and disposal facility, etc. Three main hypotheses were formulated: (1) this site is concentration of purely civilian nuclear fuel cycle facilities, (2) this is a military site and its main purpose is weapons grade nuclear material, and (3) this is a dual-purpose facility that is intended for weapons material production, but it is also a part of the civilian nuclear fuel cycle of the country. Discovery of the two outgoing electric power lines eliminated pure military site designation option. Detailed analyses of the individual facilities were performed next.

*IV.B.2. Nuclear Reactor Buildings*

Three operating nuclear reactor confinement buildings were found on the image during visual analysis. Also another possible reactor facility with the rectangular reactor containment building was discovered. Visual analysis of all suspected reactor facilities allowed determining the primary designation for each facility and some of its characteristics.

The largest reactor facility (area 2 in Fig. 18) consists of the two reactor domes and a series of support buildings. Two outgoing electric power lines originating from the building next to confinement structures suggest that this facility is a nuclear power plant. Results of the detailed analysis of this facility are presented in Fig. 19.


Fig. 19. Suspected Nuclear Power Plant.

The main signatures characterizing this nuclear power plant include two reactor confinement buildings (44.5 meters in diameter each), suspected turbine hall with containing turbines is located in the tall rectangular building to the east of the domes. There are no cooling towers around the facility. A water intake and discharge port connected to the complex shows that ocean water is used for cooling purposes. Among other characteristic signatures of the nuclear reactor is a high stack, outgoing electric power lines, and security fence.

Another reactor facility (Fig. 20) appears to be a research reactor, but could also be a plutonium production facility. It is located on the north side of the “campus” (area 6 in Fig. 18). The diameter of the confinement building is 27.8 meter, which is smaller than the power plant reactor domes. Smaller confinement building suggests that this facility is dedicated to research purposes and contains a lower-power reactor core.

There is a series of laboratory buildings around the confinement building, which looks like a small reprocessing plant, or a set of chemical laboratories. This reactor may be used for military purpose of plutonium production or possibly for various medical and industrial isotope production, including separating of fission products from the spent fuel. Another prominent feature of this facility is the presence of the cooling tower, which suggests the presence of the secondary water coolant loop. Similar to the majority of other facilities onsite, the suspected research reactor has an individual security fence line.

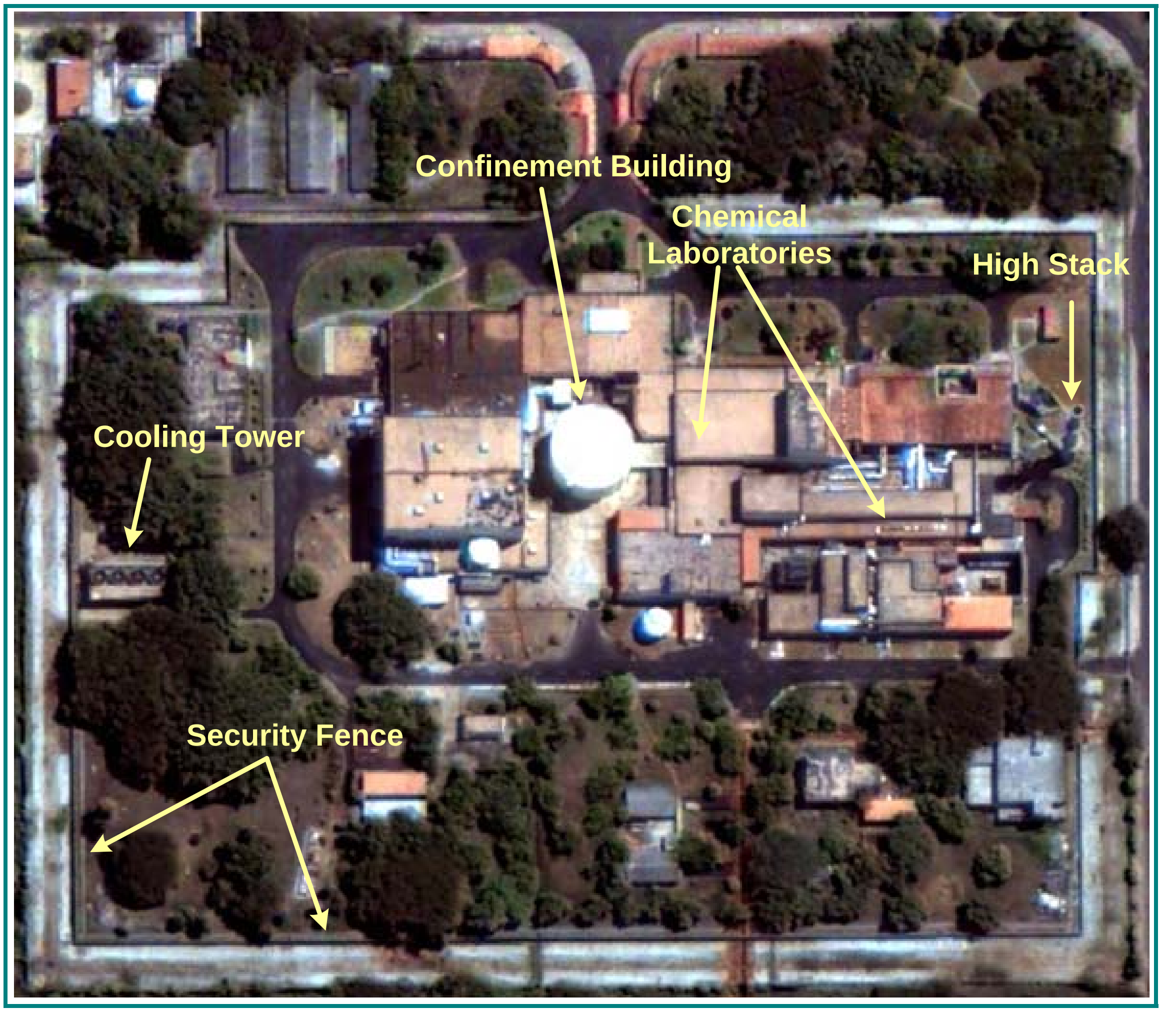



Fig. 20. Suspected Research Center / Plutonium Production Reactor.

The third suspected reactor site (area 1 in Fig. 18) is located north-east from the power plant. There are several signatures that suggest that this is potentially a reactor site. The tall rectangular buildings appear to be the confinement. There are also several cooling towers, water discharge port and a high stack for off-gas dispersal. There are no switch yard or out going power lines, which means that if this is really a reactor facility, it is dedicated to production of plutonium. The image of the suspected plutonium production reactor is presented in Fig. 21.


Fig. 21. Suspected Plutonium Production Reactor.

*IV.B.3. Nuclear Fuel Reprocessing Plant*

Several facilities in this site appear to have several signatures specific to nuclear fuel reprocessing plant. Among the signatures: large interconnected long “canyon-like” buildings, a very high stack for process off-gas release, storage tanks, and security fence line around it. The image of the largest of the suspected nuclear fuel reprocessing plants is presented in Fig. 22.

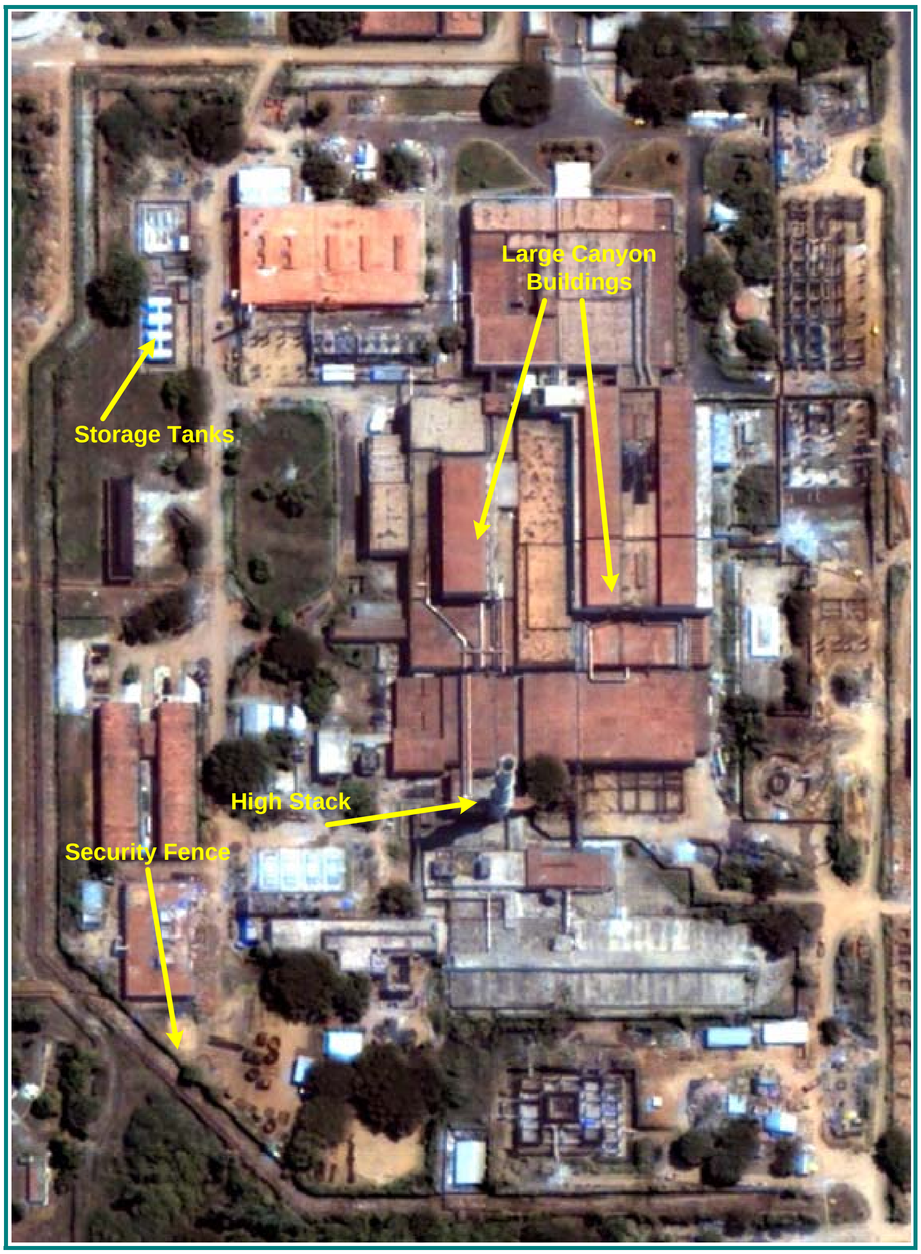



Fig. 22. Suspected Nuclear Fuel Reprocessing Plant.

The reprocessing plant may be dedicated to recycling of the spent nuclear fuel from the power plant reactors and is producing a mixture of plutonium and uranium for the mixed-oxide (MOX) fuel. Presence of several reprocessing facilities may indicate that weapons-grade plutonium production is also taking place in this site.

*IV.B.4. Waste Treatment and Storage*

Another prominent facility is a nuclear and radioactive waste treatment and disposal plant. This installment is co-located with the reprocessing plant. The main features of the facility include a set of buildings that appear to be for waste processing and segregation; several burial sites; several sediment ponds; a few wells, possibly for deep underground injection of high level radioactive waste from the reprocessing plants.

There are two types of waste burial present onsite: above ground storage in containers and underground disposal, where waste containers are covered with dirt after disposal. Different types of disposal were developed for various types of waste, depending on its activity and physical form.


Fig. 23. Suspected Nuclear Waste Treatment and Disposal Facility.

**IV.C. Conclusions**

Visual analyses of the blind case scenario image revealed the presence of several co-located nuclear fuel cycle facilities. It appears that the site performs activities covering almost the full nuclear fuel cycle. The full list of suspected facilities includes:

- nuclear power plant with two reactor units,
- research reactor,
- possibly a plutonium production reactor,
- nuclear fuel reprocessing plant,
- nuclear and radioactive waste treatment and disposal facility,
- research laboratory buildings,
- new reactor unit construction site,
- possible mining site.

No uranium enrichment facility was identified on the image. Based on that, there are several options for the nuclear fuel cycle of the country: (1) enrichment activities are taking place in a different location and (2) reactors onsite are utilizing natural uranium fuel.

Based on the visual analysis of the full site and individual facilities, a conclusion can be made that this is a dual-purpose civilian and military site. At least two reactors are used for electric power production for the surrounding area. Spent fuel from these reactors is possible being reprocessed for reuse of leftover uranium and produced plutonium in the MOX fuel or purely for plutonium extraction for military purposes.

Two other reactor facilities are used for research purposes and for plutonium production. There are no indications of these facilities producing electricity.

The results of the blind case study were compared to the known information about facilities on the image. The ground truth for the image was provided by Professor Charlton. The facility on the image appeared to be Kalpakkam Nuclear Establishment in India. This site includes Madras Atomic Power Station (MAPS) and Indira Gandhi Centre for Atomic Research (IGCAR).

Majority of the conclusions from the blind case image analysis were confirmed by the facts known about the facility. For example, suspected nuclear power plant (Fig. 19) appeared to be MAPS. It is one of the India's nuclear power plants which currently consists of two heavy-water, natural uranium reactors, with the power levels of 155 and 202 MWe. Suspected research reactor (Fig. 20) is Kamini $^{233}U$ fueled research reactor (0.03 MWt). Another facility that was identified as suspected plutonium production reactor appeared to be Fast-Breeder Test Reactor. This reactor is fueled by natural uranium and plutonium and has 40 WM thermal power. Presence of a reprocessing plant (Fig. 22) and waste treatment and disposal facility (Fig. 23) was also confirmed during comparison of the study results against the ground truth. The fact that majority of blind case investigation conclusions were confirmed serves as another proof of the applicability of defined visual signatures for identification of nuclear fuel cycle facilities.

# CHAPTER V

# USE OF PUBLICLY AVAILABLE SOURCES OF INFORMATION

## V.A. Background

Besides commercial satellite imagery and computer codes for imagery analysis there is a variety of other publicly available sources of information that can be utilized for tracking violations of the nuclear nonproliferation regime. Among those sources are: press reports, unclassified government reports, police reports and other institutions reports, watchdog groups testimonies, etc. This chapter describes the Libyan uranium enrichment centrifuge technology procurement as a case study showing the level of detail of information that can be compiled from various open sources.

## V.B. Libyan Uranium Enrichment Centrifuge Technology Procurement Program

### *V.B.1. Brief History of Libyan Nuclear Weapons Program*

On December 19, 2003 Libyan officials announced that Libya was abandoning its clandestine nuclear weapon program. The country's major facilities included a 10-megawatt light-water research reactor and a critical assembly (100 watts), both located at the Tajura Nuclear Research Center (TNRC). A number of previously undisclosed nuclear sites were disclosed, and international officials were allowed to inspect them. Almost three decades of clandestine activities preceded this disclosure.

The Libyan nuclear weapons program was started in 1970s. Among the main motives for the Libyan government to try to acquire nuclear weapon capabilities were: a response to the Israel's clandestine but widely-suspected nuclear weapon development and a desire to become a bigger player in Middle Eastern and African politics. In the beginning of the 1970s, the Libyan government allegedly attempted to purchase an assembled nuclear weapon directly from China. After those attempts were rebuffed Libya turned to Pakistan in 1977, offering financial aid and supplies of uranium from Niger and hoping to share the results of Pakistan's nuclear program. It is important to note that meanwhile, in 1975, Libya ratified the NPT (it had been signed in 1969 by King Idris, who was later deposed in a military coup) and received a Soviet 10-megawatt research reactor, which began operating at Tajura in 1979. During the following year, Libya negotiated a formal safeguards agreement with the IAEA and placed its declared nuclear facilities under international safeguards. In the late 1980s, the Soviet Union pledged to build a 440 MW power reactor in the Surt region, but those plans never materialized.

Libya voted for indefinite extension of the NPT at the 1995 NPT Review and Extension Conference and in 1996 signed the Treaty of Pelindaba together with 42 other African countries, establishing the African Nuclear-Weapon-Free-Zone (NWFZ). In 1997, the Russian Federation restarted nuclear cooperation dialog with Libya, and, in March 1998, the Russian Atomenergoeksport Company signed a contract involving the partial overhaul of the Tajura research reactor. The possibility of cooperation in construction of a nuclear power station was reportedly under discussion in 1999.

Libya's known facilities before the December 2003 announcement included the TNRC, which was constructed with the assistance of the former Soviet Union, beginning in the late 1970s. The TNRC is thought to be at the heart of Libya's nuclear activities and has been the focus of foreign technical assistance in the past. In 1984, international journalists were allowed to visit the TNRC and reported having seen various types of 'state-of-the-art' nuclear related equipment and instrumentation from Hungary, Poland, the former Soviet Union, Switzerland and the US.

The TNRC consists of numerous laboratories and facilities. One such facility is the 10-megawatt (MW), pool-type Tajura Research Reactor (IRT-R), which was constructed in 1980 and went critical in 1981, but probably did not become operational until 1983. The reactor's core was previously filled with HEU that was originally transferred from the Soviet Union, but has since been removed and replaced with low enriched uranium (LEU) under the U.S. Russian Research Reactor Fuel Return (RRRFR) Program. The TNRC also houses a critical facility that operates a 100-watt critical assembly and a TM4-A Tokamak fusion reactor. In addition the TNRC houses a nuclear metallurgy laboratory and a radiochemical laboratory with a number of hot cells that have been used to produce various isotopes, such as $^{131}I$ for medical and agricultural purposes.

The TNRC also houses a physics research centre with various facilities for conducting research on nuclear physics, solid-state physics, neutron physics, materials science and engineering, radiation biophysics and mass spectrometry. Some of these facilities contain hot cells and glove boxes that, theoretically, could have been used to carry out spent fuel analysis, isotope production and other isotope-related research activities [12].

This concludes the brief description of what was known to the world until Libyan government revelations in 2003 and beginning of IAEA inspections of previously undeclared nuclear facilities. Libya's undeclared nuclear program involved frequent movement of key equipment and nuclear material, and it relied heavily on support from foreign sources.

*V.B.2. Uranium Enrichment Centrifuge Technology*

In its pursuit to obtain a nuclear weapon, Libya chose a highly enriched uranium weapon route (Fig. 1). There are various methods to enrich uranium, one of which is through gas centrifuges. This chapter provides a description of key technologies, materials and elements necessary in order to obtain centrifuge uranium enrichment capabilities.

Isotope separation is a difficult and energy intensive activity. Enriching uranium is difficult because the two isotopes are very similar in mass: $^{235}U$ is only 1.26% lighter than $^{238}U$. Several production techniques applied to enrichment have been used, and several are under investigation. In general these methods exploit the slight differences in atomic weights of the various isotopes. Among the uranium enrichment methods developed during the nuclear era are: thermal diffusion, gaseous diffusion, gas (zippe) centrifuge, aerodynamic, electromagnetic, laser, chemical, and plasma separation. Only a few of these methods were developed to industrial scale. Gas centrifuge is currently one of the most popular and energy-efficient methods in use. A highly efficient centrifuge plant can produce 25 kilograms of weapons-grade enriched uranium using 500,000 kilowatt-hours of electricity.

Centrifuges use uranium hexafluoride ($UF_6$) as a feed material. It is a solid white material at a room temperature. At higher temperatures, $UF_6$ evaporates into a very corrosive gas, and can be used for uranium enrichment. A centrifuge for uranium separation consists of a smooth cylinder that rotates on its axis at high speeds. $UF_6$ gas is injected into the rotating cylinder from a fixed tube introduced into the center of the centrifuge from above. The gas volume follows the cylinder, rotating at the same speed: the rotating outer wall gives its speed to the gas hitting it, and this gas, in turn, gives its speed to the gas near it until all the gas is rotating as if it were a single unit. Enriched gas and depleted gas are taken out by scoops at, respectively, the top and bottom of the centrifuge cylinder. The gas is made to circulate with a flow of gas down the periphery and back up nearer the axis. The lighter gas is not taken off on the axis of the centrifuge, because the gas density there is too low. It is, instead, taken off by a scoop at a smaller radial distance from the axis than the depleted gas, which is taken off near the periphery [48].

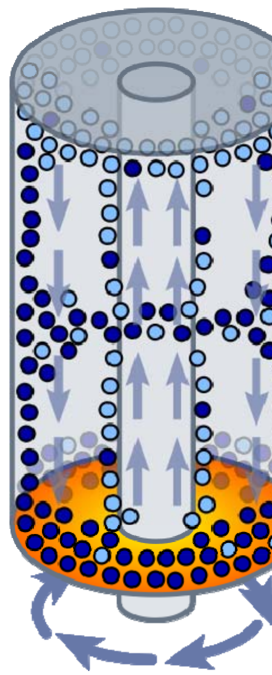


Fig. 24. Zippe-Type Centrifuge Diagram [49].

Fig. 24 shows a diagram illustrating the basic principle behind a Zippe-type gas centrifuge for enrichment of uranium. Here the heavy isotope of uranium ($^{238}U$) is represented in dark blue, while the lighter isotope of uranium ($^{235}U$) is represented in light blue. The input gas (here represented as a fairly even mix of $^{235}U$ and $^{238}U$, though in reality natural uranium hexafluoride would have less than 1% of $^{235}U$ in it) is released into the center of the centrifuge and the centrifugal forces force the heavier gas to concentrate at the edges of the centrifuge and the lighter gas at the center. By heating the bottom of the centrifuge the lighter gas will be moved by convection currents to concentrate at the top while the heavier gas will concentrate at the bottom (scoops, not shown, would then extract the gases). Here the effect is greatly exaggerated for conceptual simplicity; in reality it would be very subtle and it takes thousands of centrifuges linked together to enrich any substantial amount of uranium to any substantial amount of enrichment [49].

The centrifuge cylinders would have to be made with great accuracy, and be of very strong material. Assembly would require special techniques, such as electron-beam welding. Because of the corrosive nature of $UF_6$, all components that come in direct contact with $UF_6$ must be fabricated from, or lined with, corrosion-resistant materials [50].

The primary limitation of the rotor wall speed is the strength-to-weight ratio the rotor material. Suitable rotor materials include alloys of aluminum or titanium, maraging steel, or composites reinforced by certain glass, aramid, or carbon fibers. At present, maraging steel is the most popular rotor material for proliferators. With *maraging steel*, the maximum rotor wall speed is approximately 500 m/s. Fiber-reinforced composite rotors may achieve even higher speeds (advanced design carbon fiber rotors can exceed 600 m/sec). Another limitation on rotor speed is the lifetime of the *bearings* at either end of the rotor. Rotor length is limited by the vibrations a rotor experiences as it spins. The rotors can undergo vibrations similar to those of a guitar string, with characteristic frequencies of vibration. *Balancing of rotors* to minimize their vibrations is especially critical to avoid early failure of the bearing and suspension systems. Because perfect balancing is not possible, the suspension system must be capable of damping some amount of vibration. One of the key components of a gas centrifuge enrichment plant is the *power supply (frequency converter)* for the gas centrifuge machines. The power supply must accept alternating current (ac) input at the 50- or 60-Hz line frequency available from the electric power grid and provide an ac output at a much higher frequency (typically 600 Hz or more). The high-frequency output from the frequency changer is fed to the high-speed gas centrifuge drive motors (the speed of an AC motor is proportional to the frequency of the supplied current). The centrifuge power supplies must operate at high efficiency, provide low harmonic distortion, and provide precise control of the output frequency [45].

Also very important from the safety standpoint is *centrifuge casing*. A single centrifuge casing can enclose one or numerous rotors (depending on the centrifuge design), and is needed in maintaining a vacuum to facilitate the flawless operation of these rotors. The casing's secondary role is to contain exceedingly fast spinning components is case of a centrifuge malfunction. If not contained, shrapnel from one centrifuge breakdown can destroy adjacent centrifuges and in essence start a harmful chain reaction within a cascade [51].

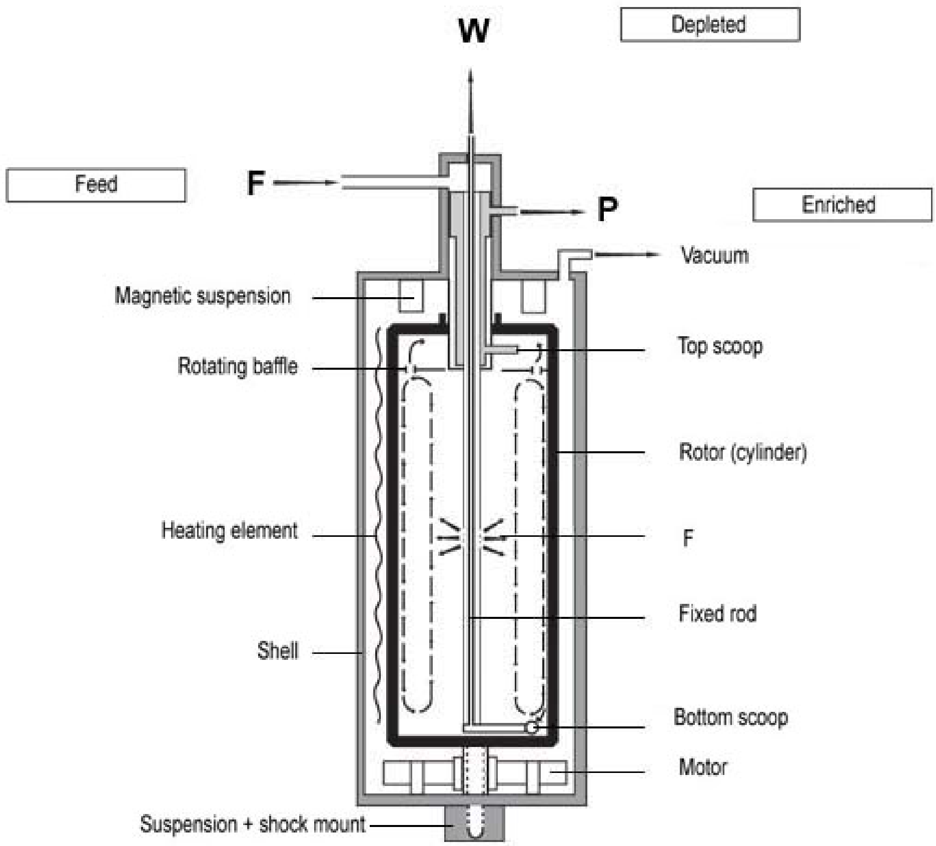



Fig. 25. Schematic of a Typical Uranium Enrichment Gaseous Centrifuge [52].

A schematic representation of the typical uranium enrichment centrifuge is presented in Fig. 25. Pakistan's nuclear program developed the P1 and P2 centrifuges – the first two centrifuges that Pakistan deployed in large numbers. The P1 centrifuge uses an aluminum rotor, and the P2 centrifuge uses a maraging steel rotor. These centrifuges are made of approximately 100 components that can be broken down into the following categories:

1. very high precision rotors of material of very high tensile strength
2. ring magnets

3. non-corrosive pipes and valves
4. end-cap
5. baffle
6. specially crafted bearings
7. damping systems
8. containers
9. motors
10. pumps
11. flow valves
12. flow-meters
13. high-vacuum pumps
14. power supply (frequency changer).

Because the enrichment output of a single gas centrifuge is insufficient to obtain significant uranium enrichment, several hundred or even thousands of gas centrifuges are linked together in what is known as cascade. A cascade is the basic building block of a gas centrifuge enrichment facility. This allows $UF_6$ gas to pass through a successive number of centrifuges in various cascades and gradually this process leads to increased enrichment of the $^{235}U$ to the desired enrichment level.

*V.B.3. Libya's Enrichment Technologies Procurement Timeline*

Libya started developing its uranium enrichment program in the 1980s. At least two facilities were built to conduct centrifuge research and development: the original testing facility at Al Hashan; and the newer research facility at Al Khalla. Later the project *Machine Shop 1001* was constructed to assemble centrifuges. During the 1980s, Libya's scientists worked with a 'European expert with relevant experience' (possibly Karl Heinz Schaab) to design a gas centrifuge. The expert brought a centrifuge design with him to Libya, and worked with the Libyans to develop two types of centrifuges. Libya was interested in both 'L-1 and L-2 type' centrifuges (presumably the same as Pakistani P-1 and P-2 centrifuges). Although they were not successful in building a working centrifuge system, Libya did gain experience in designing and operating centrifuge equipment and related technologies [53].

In 1997 Libya had contacted Dr. Abdul Qadeer Khan to obtain help and expertise in the field of uranium-enrichment centrifuge technology. Khan Research Laboratories (KRL) – the main entity in Pakistan that was in charge of national nuclear program development. The program was started in 1970s. Dr. Khan was the key figure in the development of Pakistan's nuclear program. In his quest for nuclear technologies he created a worldwide network of nuclear technology suppliers. Dr. Khan used his contacts and resources of his laboratory for his personal profit.

During the period of 1997-2002, a series of meetings between Khan and representatives of Libya – Mohamad Matuq Mohamad and Karim took place in Istanbul (Turkey), Casablanca (Morocco) and Dubai. The results of these meetings were a $100 million contract for the supply of centrifuge components and an "off the shelf" gas centrifuge manufacturing plant. Allegedly Khan also provided Libya with design of the nuclear warhead, free of charge as a "deal sweetener". Supposedly most of that data were for a 10-kiloton warhead with a mass of 500 kilograms that would not have fit on Libya's SCUD missiles, but could have been delivered through other means.

In 1997 Libya purchased ten assembled P-1 centrifuges from Khan Research Laboratory (KRL). These centrifuges were previously decommissioned from Pakistan's nuclear program. Shortly after that Libya purchased components for about a 100 additional P-1 centrifuges. Furthermore, Libya attempted to procure advanced P-2 centrifuges. Two P-2 centrifuges and components for a few more were sent to Libya in September 2002 as demonstration models. Libya placed an order for 10,000 more P-2 centrifuges shortly after receiving demonstration units. Since each centrifuge consists of more than a 100 components, the order required approximately one million components. Libya's final goal was to create a 10,000 centrifuge cascade for producing HEU that could be used in nuclear warheads. After starting the cascade Libya would have the capability of producing enough material for 10 nuclear weapons annually.

Simultaneously with the attempts to purchase centrifuges Libya was working on building its own gas centrifuge production capabilities. This project had a codename "Machine Shop 1001". The main objective of the project was to manufacture components in Libya and build additional centrifuges after the initial shipments of 10000 centrifuges had been delivered. The initial plan included detailed plant design information, electrical and electronic equipment, 20 tons of $UF_6$, and feed and withdrawal equipment for uranium. Most of the equipment for "Machine Shop 1001" including furnaces, machine tools, and other equipment came from different European countries, particularly from or through Italy and Spain. The majority of this equipment was sent to Libya through Dubai. Acquisition of equipment for “Machine Shop 1001” involved other alleged Khan nuclear black market associates, including British citizen Peter Griffin, former owner of Gulf Technical Industries (GTI) in Dubai, and German citizen Gotthard Lerch, former employee of Leybold Heraeus, a German vacuum technology manufacturer [51]. Information about countries, companies and individuals involved in providing help to Libya in its quest for nuclear weapon capability is summarized in Table XI.

TABLE XI

Summary of Key Players of AQ Khan’s Nuclear Black Market Involved in Libya’s Gas Centrifuge Technology Procurement

| Country | Company | Person | Parts | Comments |
|---|---|---|---|---|
| China | | | Uranium Conversion Facility | |
| Dubai | SMB Computers | BSA Tahir | | Several equipment transfers to Libya were conducted through SMB Computers. |
| | Gulf Technical Industries (GTI) | Peter Griffin | | GTI is a company in Dubai, which belonged to Peter Griffin and was used for reexporting of several items to Libya. |
| France | Cazeneuve | | CNC Lathe Mexica 590 | Machine for Scope purchased from France |
| Germany | Leybold Vacuum GmbH | Gotthard Lerch | pipes for the Machine Shop 1001 | have tried to obtain supplies of pipes for the Machine Shop 1001 Project by sourcing from South Africa but failed to obtain it even though payment had been made by Libya earlier |
| | | Karl Heinz Schaab | | gas centrifuge specialist, involved with Iraq |
| | | Heinz Mebus, an engineer | | |
| | Ship BBC China owned by German company | | | on 4 Oct 2003 was examined in the port of Taranto, ITALY, where 5 containers were confiscated because they were believed to contain components related to the Libyan uranium enrichment program |

TABLE XI (continued)

| Country | Company | Person | Parts | Comments |
|---|---|---|---|---|
| Great Britain | | Peter Griffin | Italian – made furnace, lathe machine | Alleged to have supplied the lay-out plan for the Machine Shop 1001 as a workshop to enable Libya to produce centrifuge |
| | | | CNC Lathe Hawk (Cincinnati), CNC Machining Center Arrow 500 (Cincinnati), Emco PC Turn 155 | Machines for Scope were bought from Great Britain |
| Italy | | | Machine tools and furnaces | |
| Malaysia | Scomi Precision Engineering SDN BHD (SCOPE) | | Outer casing (P2), molecular pumps (P2), top spacers (P2), positioners (P2), top ends (P2), crash rings (P2), stationary tubes (P2), clamp holders (P2), flanges (P2) | BSA Tahir allegedly commissioned SCOPE factory to manufacture centrifuge components for delivery to Libya. A total of 25,000 centrifuge components were manufactured for Libya. |
| | | BSA Tahir (Buhary Seyed Abu Tahir) | | BSA Tahir was AQ Khan's right-hand man. Participated in meeting between AQ Khan and Libyans. |
| Pakistan | Khan Research Laboratory (KRL) | A. Q. Khan | 1.7 tons of $UF_6$, 92 assembled P-1 centrifuges, Parts for additional 128 P-1 centrifuges, Two P-2 centrifuges, Additional parts for several P-2 centrifuges, Design for a nuclear warhead assembly. | Head of international nuclear black market |
| Switzerland | CETEC | Friedrich Tinner | | CETEC was reported to have prepared certain centrifuge components, including safety valves, and he sourced many of the materials that were made in several companies in Europe. |
| | Vakuum-Apparate-Technik (VAT) | Friedrich Tinner | | VAT was identified by the Swiss Defense department as involved in shipping possible nuclear related items to Iraq and Pakistan |
| | | Urs Tinner (son of Friedrich Tinner) | | Helped to set up the SCOPE factory. He was actively involved in the manufacturing operations in the SCOPE factory. He controlled much of the centrifuge design for AQ Khan's network. |
| | Traco Company | Marco Tinner (son of Friedrich Tinner) | | Traco was responsible for the export of flow forming equipment for Machine Shop 1001. Traco was used for importing key cutting and grinding machinery to SCOPE |
| Taiwan | Monaset | | Universal Tool Grinder | Machine for Scope purchased from Taiwan |
| Turkey | ETI Elektroteknik | Gunas Jireh | Power supply components; ring magnets; aluminum casting and dynamo. | ETI Elektroteknik is a Turkish electronics company. ETI's director Gunas Jireh is a former employee of Siemens in Germany. |
| | Elektronik Kontrol Aletleri (EKA) | Selim Alguadis | electrical cabinets and power supplier-voltage regulator | Selim Alguadis, the president of EKA, is a Turkish engineer who has reportedly been in contact with AQ Khan since 1980s. |

*V.B.4. Key Players of the Procurement Network*

Libya's successful procurement of uranium enrichment centrifuge technology was possible due to the international procurement network headed by the "father of Pakistani atomic bomb" Abdul Qadeer Khan. Pakistan's need to produce nuclear weapons became urgent after India tested its nuclear weapon on 18 May 1974. In view of this, the Kahuta Plant was set up and the Khan was forced to get equipment discreetly from developed nations, especially those in Europe. In the process, he developed contacts to get the needed material from several countries. This had to be done discreetly because Pakistan had to develop a nuclear weapon for national defense after India's nuclear test received opposition from many Western countries. Amid these difficulties, Khan successfully developed a network of middlemen that involved several people and companies from Europe, the Middle East, and Asia seeking to make profits by selling certain materials and equipment. However, it was a loose network, without a rigid hierarchy, or a head and a deputy head as was alleged.

Several key figures played the major part in this network. Detailed information about most of the key individuals involved in Khan's network collected from various open sources is available. Only several network operatives are described in this chapter to demonstrate the level of detail that can be found and compiled.

*BSA Tahir* whose full name is Buhary Seyed Abu Tahir (Fig. 26), is a citizen of Sri Lanka and a businessman based in Dubai. BSA Tahir and his brother own a company named SMB Group, Dubai, where he is the Group Managing Director. In 1998, BSA Tahir married a Malaysian woman and gained permanent residency in

Malaysia. SMB Group started as a family company in 1980 and is now involved in the computer and IT fields. Generally, BSA Tahir spends time overseeing his businesses in Dubai and only returns to Malaysia, once in a while, to visit his wife's family or look for business opportunities. Upon his father's death in 1985, BSA Tahir took over the management of SMB and in the process visited Pakistan and succeeded in getting contracts to sell air conditioning equipment to KRL. During this time, BSA Tahir became acquainted with Khan. At the same time, BSA Tahir got to know middlemen from other countries, including Europe, who were involved in supplying uranium centrifuge components on behalf of Khan [54].

Fig. 26. Buhary Seyed Abu (BSA) Tahir

*Urs Tinner* whose full name is Urs Friedrich Tinner is the son of Friedrich Tinner, the president of CETEC company in Switzerland who allegedly had dealings with AQ Khan since 1980s. Urs Tinner had been a full-time technical consultant to SCOPE starting April 2002. As a consultant, Urs Tinner was responsible in importing and setting up the machine that was bought through the services of his father, Friedrich

Tinner. There were also machines imported through Traco Company, Switzerland, owned by Marco Tinner, the brother of Urs Tinner. Among the types of machines bought and fixed by Urs Tinner were:

- CNC Lathe Hawk (Cincinnati), United Kingdom,
- CNC Machining Center Arrow 500 (Cincinnati), United Kingdom,
- CNC Lathe Mexica 590 (Cazeneuve) in France
- Emco PC Turn 155, United Kingdom
- Automated Bandshaw Cutting Machine (Averizing), Taiwan
- Universal Tool Grinder (Monaset), Taiwan.

Urs Tinner ended his term of service at the SCOPE factory in October 2003. Just before this, he had taken the hard drive of the company's computer that was designated for his use. Urs Tinner also had taken his personal file from the SCOPE factory's records. According to testimonies of several SCOPE staff, Urs Tinner erased all technical drawings that were kept in the computer at the SCOPE factory. This gave the impression that Urs Tinner did not wish to leave any trace of his presence there and wanted to ensure that the technical drawings did not fall into the hands of the SCOPE factory staff. However, Urs Tinner left behind a machine, i.e., a manual turning machine. It was a 1948 model made in Schaublins, Switzerland. This machine was never used

*V.B.5. Sources of Information Used During Investigation*

All information described in this chapter was obtained solely from publicly available sources of information and unclassified government reports. Data were thoroughly collected and reviewed. Various pieces of information were put together to create a comprehensive picture of the Khan's network relations with Libya and some of the network operatives involved in materials and technology transfers to Libya.

A large number of press reports and news releases were used, some of these reports contained interviews with the middlemen involved in activities supporting Libya's weapons program. The majority of the information was compiled from news articles and radio interviews such as Time Magazine, Africa News, Johannesburg SAPA, Al-Sharq al-Awsat and many others. Press reports and news coverage archives from United States, South Africa, South Korea, Malaysia, Great Britain, and United Arab Emirates were used during this investigation. The full list of press sources is compiled in Table XII.

TABLE XII

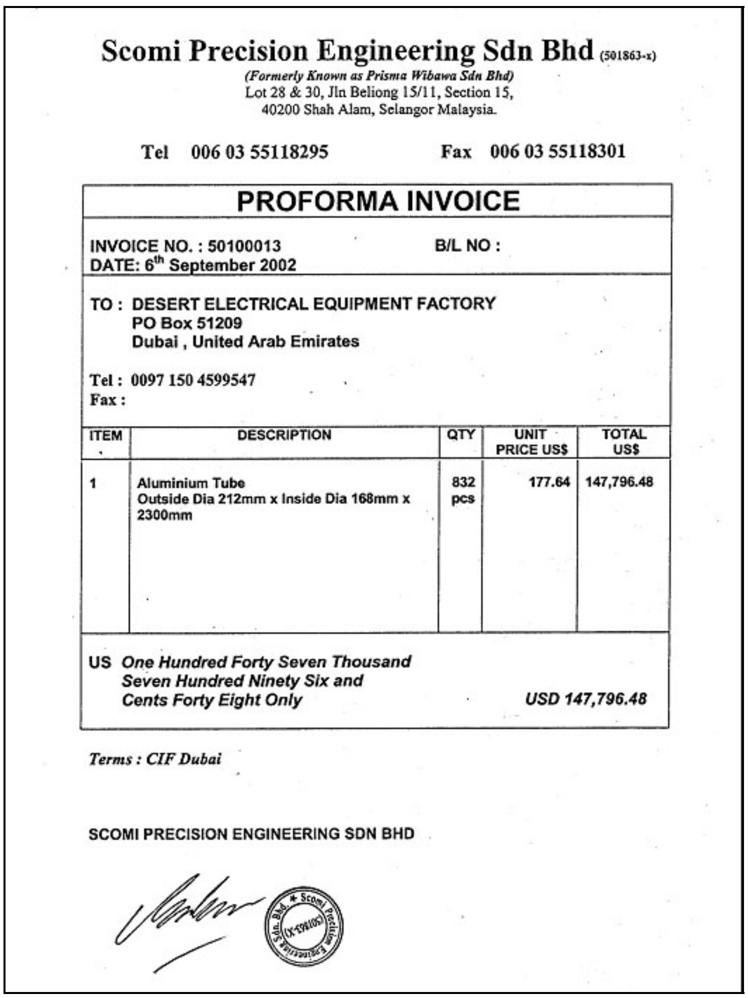
Press Report and Articles Used for Libya Case Investigation.

| News Paper of Press Agency | Reference Number |
|---|---|
| Africa News | [55] |
| Agence France-Presse (AFP) | [56], [57] |
| Al-Sharq alAwsat | [58] |
| Arab News | [59] |
| BBC | [60] |
| Dawn | [61], [62] |
| Financial Times | [63], [64] |
| Johannesburg SAFM Radio | [65] |
| Johannesburg SAPA | [66], [67] |
| Johannesburg This Day | [68] |
| Korea Times | [69] |
| Los Angeles Times | [70] |
| NIS Export Control Observer | [71] |
| The Associated Press | [72] |
| The New York Times | [73], [74], [75] |
| Time Magazine | [76] |
| United Press International | [77] |
| Washington Post | [78], [79] |
| Washington Quarterly | [80] |
| Washington Times | [81] |
| Wolgan'gongjakkigye | [82] |
| Yonhap | [83], [84] |

A very important part of the investigation is the historical and technical country profile. This information helps in understanding the motives of the country starting its covert nuclear weapons program, its initial scientific and technical capabilities, and also amount of resources available. Based on this assessment, a level of foreign assistance that was needed can be estimated. In addition to historical data various technical papers and grey literature resources were used to obtain detailed information about centrifuge uranium enrichment technology and particularly about Pakistani designs of the P-1 and P-2 centrifuges.

Information from international customs services allowed tracing shipments of various centrifuge parts. Several countries and companies involved in production and then transfer of the centrifuge parts to Libya were revealed as a result of shipping paperwork analysis. Some of the companies were just intermediaries providing a shipping address to avoid direct shipments from the producer to Libya, and could possibly be involved in transactions with other suspected proliferators. Another important piece of information that allowed estimating the scale of the Libyan nuclear program, is the quantity of shipped materials and parts. As an example, one of the SCOPE's packing lists for the shipment of aluminum tubing to one of the intermediary companies in Dubai is presented in Fig. 27.

An important resource for this investigation is the report by Malaysian police, which was published on February 20, 2004 [54]. The report was compiled on the request of American and British intelligence services, as a part of investigation of activities of Sri Lankan businessman's BSA Tahir, who ordered centrifuge components manufactured by SCOPE. The report covers the timeline of production activities at SCOPE, the involvement of outside individuals involved in placing the order, and the identification of the supervision of the manufacturing process. Company's management admitted making centrifuge components at the factory, but they stated that SCOPE was not aware of parts' final destination and that they believed these parts were for the oil and gas industries.



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**PROFORMA INVOICE**

INVOICE NO. : 50100013 B/L NO :
DATE: 6th September 2002

TO : DESERT ELECTRICAL EQUIPMENT FACTORY
PO Box 51209
Dubai , United Arab Emirates

Tel : 0097 150 4599547
Fax :

| ITEM | DESCRIPTION | QTY | UNIT PRICE US$ | TOTAL US$ |
|---|---|---|---|---|
| 1 | Aluminium Tube<br>Outside Dia 212mm x Inside Dia 168mm x 2300mm | 832 pcs | 177.64 | 147,796.48 |

US *One Hundred Forty Seven Thousand Seven Hundred Ninety Six and Cents Forty Eight Only* *USD 147,796.48*

*Terms : CIF Dubai*

SCOMI PRECISION ENGINEERING SDN BHD

Fig. 27. SCOPE Packing List for Aluminum Tubing Shipment to the Intermediate Company in Dubai [54].

### V.C. Conclusions

In this chapter a detailed full-scope overview of Libya's procurement of uranium enrichment centrifuge program was provided. A historic outline of Libya's declared nuclear program is combined with the timeline of the undeclared-at-the-time procurement of centrifuge technology and components. Key figures of Khan's nuclear black market, and also of companies around the world, who were directly and indirectly involved in this covert program are also listed and described.

Open-source investigation of Libya's procurement of uranium enrichment centrifuge technology is one of the examples of successful analysis of a violation of nuclear nonproliferation regime. An impressive level of detailed information that was collected proves the feasibility of a community of academic research groups performing similar open-source investigations.

# CHAPTER VI

# INTEGRATION OF INFORMATION FROM ALL AVAILABLE SOURCES

## VI.A. Introduction

Open-source analysis is an essential component of nuclear nonproliferation verification. Recent advancements in world-wide communications and data access provide extensive capabilities for organizations and individuals around the world for data search, exchange and analysis. High-resolution commercial satellite imagery offers views of virtually any location on Earth with resolutions from less than one to five meters. An expanding wealth of open-source information is being published in both commercial and public databases, both in hard-copy or online. Interested parties may acquire the imagery and open-source information through direct purchase or indirectly through research services. Civil groups, like INMAC, may use this new range of resources either to support or to challenge verification and compliance procedures for several disarmament treaties including NPT.

During open-source information analysis, the most effective results can be obtained from the integration of data from all available sources of information. This chapter covers a wide variety of topics: the proposed structure of the community of academics; educating members and means of interaction between and among them; several possible open-source investigation scenarios; information analysis techniques, and data integration mechanisms for collaborative open-source investigation by a community of academics. Suggested methods of compiling data from all available sources of information would allow extraction of the most detailed information about the proliferator's intentions, capabilities, and weapons program scale.

### VI.B. Proposed INMAC Structure

For a large international community of academics, one of the key requirements for effective information search and analysis is the well-organized interaction and data exchange among its members. Operational structure of the organization would define the ways for collaboration between the academic community members.

INMAC structure is proposed as a set of peers (research groups) around the world. These groups would be created by the subject matter experts or specific institutions. Besides performing pure search and analysis tasks, one of the goals of the community and individual teams is development of innovative methods of data search and analysis. To fulfill this goal, specialization in particular sources of information or analysis types for each individual group would be desired, but it should not be a hard requirement or a limiting factor.

Research groups would be formed by the geographic location or by the area of interest/expertise. Example of the first option would be a situation, when a subject matter expert in a particular institution or geographic area creates a group of his/her students or co-workers. Members of the second type of a group would not be co-located geographically, but would be united by the interest in the same subject. Subject matter experts would educate members of their research groups and lead various projects carried out by the group.

Another kind of educational activities would be topical forums and workshops that could be organized for interested members of the community. During these workshops, analysts would meet with each other and find others with similar areas of interest, present results of their research, exchange experience, and develop new open-source analysis methods and strategies. Knowledge and experience transfer will not only expand the number of experts and community workforce, but also guarantee knowledge retention and expansion.

Created research groups would be able to exchange information and experience via the centralized server. It would provide storage for the collected information and data analysis. Most of the communication between members of the community would be carried out in the form of a blog or a forum. Blogs with different topics would be started by society members and would be accessible for review, comments, and adding of new information by all society members and groups. New data or analysis results would be added to the appropriate topic or topics if there are several related threads. Some of the groups would provide information verification and information integrity confirmation.

**VI.C. Examples of Possible Investigation Scenarios**

Historically most of the covert nuclear weapons programs became known to the world as a result of intelligence or criminal investigations of international nuclear black market activities (Libya) or through watchdog groups' revelations (Iran). After discovery of an illegal weapons' program, satellite imagery, press and police reports, and other available data, is used for recreating the full scope of illegal activities. For example, in the case of Iran, its nuclear weapons program was revealed by one of the internal exile groups, which stepped out and provided information about some of the activities that were taking place inside the country. Then, independently from government intelligence agencies, several research groups and nonproliferation policy institutes discovered a number of suspicious facilities and construction sites (Natanz, Isfahan, etc.) using high-resolution commercial satellite imagery. Furthermore, customs data and an investigation of Khan's international nuclear black market network revealed even more details about the program.

There are several potential routes for open-source information investigation and for building a chain of documents and data leading to comprehensive scope of a proliferator's real intentions. None of those scenarios can be universal or optimal for investigation. Each particular case may be initiated by information from a specific source and should be treated individually from there. However, in order to set up a universal monitoring system there should be several sources selected for constant surveillance. Use of such a system will allow early discovery of any type of illegal activities and initiate a full-scale investigation involving all resources available to INMAC. Satellite imagery, watchdog groups reports and customs information are suggested as such "constant monitoring" resources.

*VI.C.1. Satellite Imagery Scenario*

The use of commercial satellite imagery would allow detection of suspicious facilities around the globe with the help of sets of signatures specific to various nuclear fuel cycle facilities. In case of global monitoring, high-resolution imagery has limited application because of several reasons. First, huge arrays of data that are needed to cover all areas of interest, which in turn lead to a demand in enormous storage space and calculation power. Second, large financial resources that would be needed to maintain an up-to-date library of high-resolution imagery. Because of these disadvantages, a use of lower-resolution multispectral or hyperspectral data is proposed. These data can be updated on a regular basis at a smaller expense and can be used as a feed for change-detection algorithms. Areas where some significant changes are found can be further investigated for the presence of construction sites or newly built facilities with the help of high-resolution imagery. If a new facility or construction site is found, it should be first investigated for the presence of nuclear fuel cycle facility signatures. After that, local and national press-reports related to the area of interest should be browsed for announcements or any articles related to the new facility construction. Watchdog reports can provide more details about the true intention of the facility under construction. The next should be uncovering all suspicious shipments to the country and to the area using customs information.

*VI.C.2. Watchdog Group Scenario*

In a case when the first information about illegal nuclear weapons related activity is reported by one of the internal watchdog groups, some level of details about the program or facilities is usually provided in the initial report. As the next step, all available sources should be used to confirm the credibility of watchdog revelations. An extensive study of a high-resolution satellite imagery of the area identifying signatures specific to nuclear-fuel-cycle facilities should be conducted. Announcements and articles related to the area's industry development in the local and national press should be checked. Also an extensive search for any suspicious shipments and transactions should be performed using customs information.

*VI.C.3. Customs Information Scenario*

In this case investigation starts after discovery of several suspicious shipments to a particular country or area. Information available includes preliminary information about the types of materials and machinery procured by the state. This information may only provide an idea about possible facility type (chosen route, see Fig. 1). Satellite imagery and watchdog revelations can be used for locating an actual facility or construction site and for final confirmation of real intentions of a potential proliferator.

All described scenarios are similar to each other and ultimately engage all available resources in order to obtain as much information about suspected nuclear weapons program as possible. Effective monitoring for suspicious activities is one of the most important parts of successful nonproliferation regime verification. Monitoring activities will be the major part of academic community operations. Ideally, in a proliferation-free world, it would be the only activity carried out by all monitoring and intelligence organizations and interested watchdog communities.

## VI.D. Proposed Investigation Algorithm

In the previous section several possible investigation scenarios and open sources of information suitable for constant monitoring of suspicious covert activities were defined. Based on described information, investigation algorithm should be selected for the effective collaboration and exchange among members of the academic community.

This section describes the main phases or steps of the open-source investigation by the community of academics. Defining and separating these steps would provide structure to the interactions between and among various research groups within the community, would help in preventing the performance of same task by different groups, and would also provide a mechanism for effective data quality verification. A graphic flowchart of the proposed algorithms is presented in Fig. 28.

The first stage of the process is selection of the country of interest and creating a plan for information collection. Continuous monitoring of several open sources of information that were proposed in the previous section would be performed on the first phase of the investigation. The actual investigation would start when one of the surveillance groups detects suspicious activities in one of the countries around the world. At this point planning of future activities would be performed. Because of the peer (non-hierarchical) structure of the community, the investigation plan would primarily identify (1) goals, i.e. what needs to be found or proven, (2) potential sources that can be used in order to achieve these goals, and (3) the approximate timeline for the investigation.

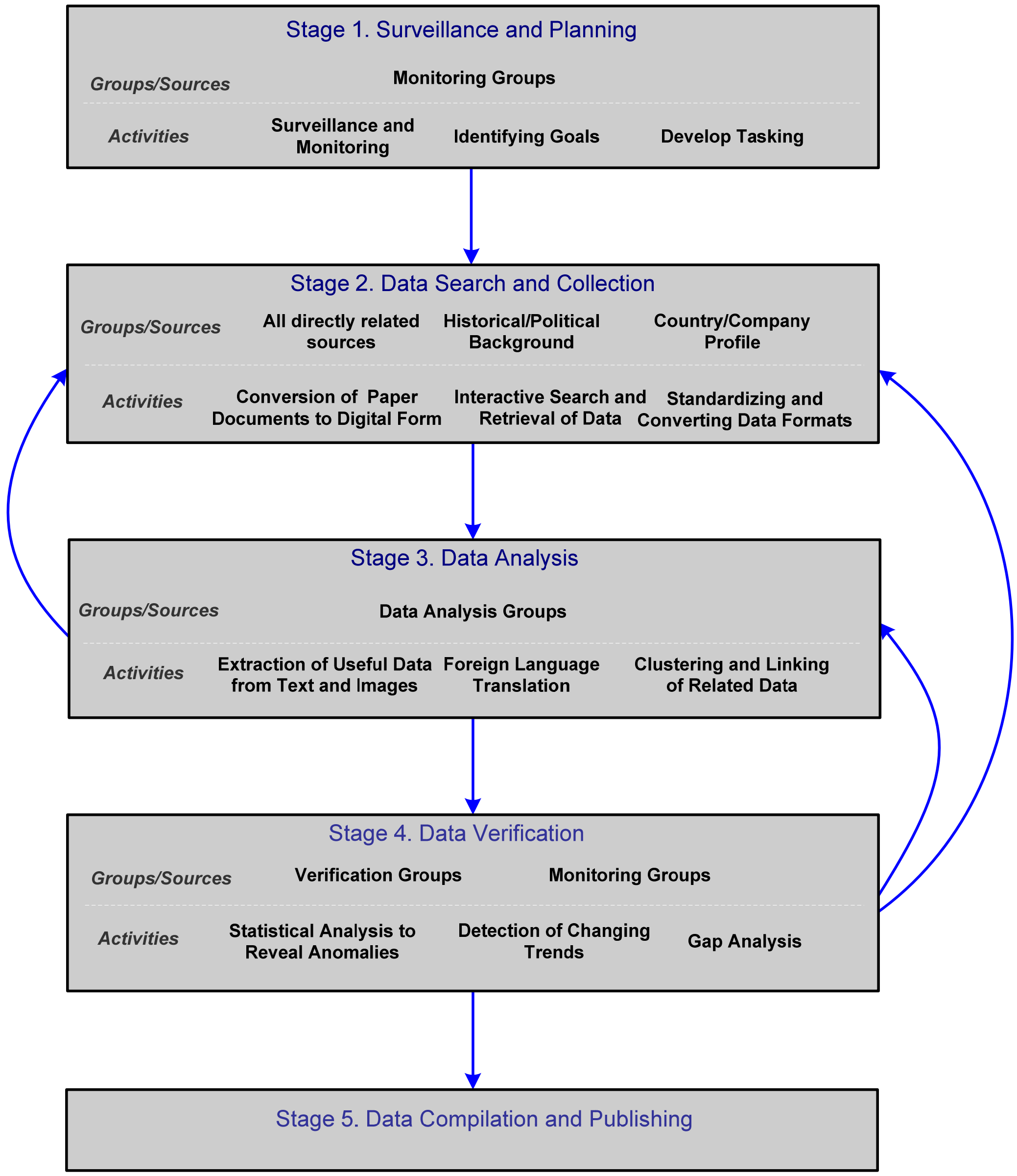


Fig. 28. Proposed Investigation Algorithm Flowchart.

At the second stage, an extensive information search would be started. All appropriate directly related sources would be used for identification of countries, companies, and individuals involved. Satellite imagery would be used to find and analyze capabilities of nuclear fuel cycle related facilities. The historical and political country profile would be studied to identify the country's geopolitical concerns, internal regime and international relations. Also at this stage all found information would be structured and converted into a pre-defined standard format and all paper documents would be converted into electronic form for structures filing and retrieval.

Stage three is defined as data analysis. At this stage research groups within the community specializing in data analysis would be engaged. Segregation and sorting of useful data from text and picture documents would be performed. If applicable, satellite imagery of suspected covert nuclear facilities would be studied for specific signatures and characteristics. All information found in languages other than English would be translated. The ultimate goal of this phase is clustering and linking related data. At this point, if analysts would determine the lack of or poor quality of data, they may request more information collection in a specific area or from a specific source.

The next phase is dedicated to the verification of collected information. Special data verification groups would apply statistical methods to reveal anomalies in collected and analyzed data, verify credibility of the sources used, and perform gap analysis to determine areas where more information collection is necessary.

The last stage consists of data compilation and report publishing. The final report may be a group effort of all participants or it may, for example, be primarily created by the group that first discovered a suspected violation. Resulting publication would contain a set of conclusion about the country's or countries of interest nuclear weapons program, current development stage, acquired technology, etc. The logic behind any conclusion should be convincing and be supported by the facts from the identified and confirmed sources.

A proposed algorithm defines a general framework for the process of information collection and analysis by an international community of academics. All stages of the investigation process are closely related to each other and activities within these may overlap. Also these stages of investigation usually would not be separated by any specific timeframes and the vast majority of activities would be taking place at the same time. The main goal of identification of specific stages and steps is organizing and structuring functions of various research groups within the community and interactions between and among them.

### VI.E. Information Collection, Analysis, and Storage

The variety of sources that may potentially be used during the investigation by the community of academics and members with a wide variety of expertise suggests the necessity for the unified procedure for interaction and information exchange between and among different research groups within the community. The community will consist of groups specializing in different sources and analysis. All groups will exchange information as needed and also all data will be accumulated in a structured format within the central server.

Defining an effective interaction mechanism between and among members of the academic community is one of the primary tasks and conditions for the successful implementation of monitoring activities by the community. According to the proposed-above structure of the organization it would consist of a number of research groups formed at particular geographical locations and/or by the area of interest and expertise. The centralized data storage and information exchange server would be designed to connect all groups together and provide the means of communication between and among members.

There are several main characteristics of the investigation conducted by the academic community:

1. all information will be accumulated on the central server;
2. individual investigations can be created in a form of a thread in the blog (forum) on the server by any member of the society;
3. each investigation would consist of a number of blocks similar to the steps of the classic nuclear fuel cycle;
4. the number of blocks and specific activities included in each block would be determined by the creator of a thread and later can be modified;
5. each member or research group would be able to access various threads and add documents, data analysis results, etc., as appropriate in relation to a particular block of a thread;
6. all information and data analysis results would be assessed for credibility and relevance to the subject of investigation, a data confidence index would be calculated to assess information quality within each block;
7. figure of merit would provide estimated progress of the suspected country in creating a weapons-production nuclear fuel cycle, assessment would account for the credibility and consistency of the results and conclusions;

8. based on conclusions and results, a credibility assessment results report would be prepared to describe findings and suspected activities in a country that is the subject of the investigation.

*VI.E.1. Central Server Information Storage Structure*

The following structure is proposed for individual investigation threads on the central server. Once there is a suspicion about an illegal activity in a country, a research group or a member creates a new thread on the central server. The creating user defines specific blocks that describe the path and suspected activities in the country. In general these blocks would follow classic steps necessary for acquisition of nuclear weapons' capabilities described in Chapter I (e.g. uranium milling, uranium conversion, acquisition of uranium enrichment centrifuge technology, etc.). An example of a possible investigation thread structure is presented in Fig. 29. If the actual path is not clear after the first detection of suspicious activities, additional blocks would be added during the investigation when more information is available.

Community members accessing the central server would be able to look through the information in each section of the investigation, add new documents, analyze data collected by other members and groups and provide analysis results, and also discuss findings and results with other members of the community. Specific database format would be developed to accommodate effective storage and display of information from different sources and of different nature.

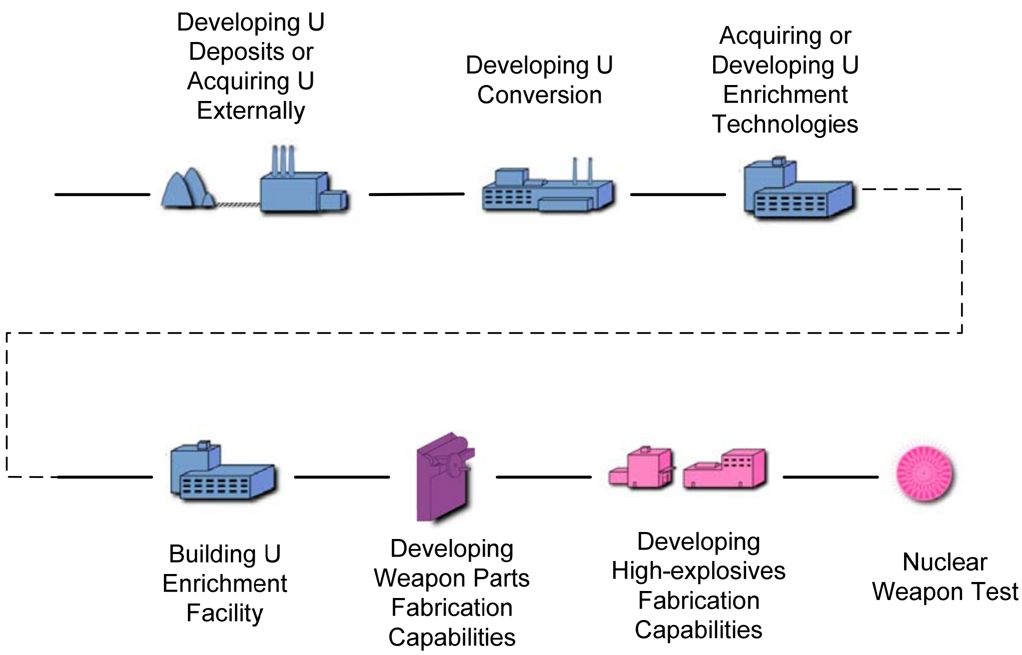


Fig. 29. Example of a Hypothetical Investigation Thread Structure.

Among the advantages of the block/step structure for the open source investigation are: (1) it allows members to add information about a particular step or activity taking place in the country of interest, instead of attempting to combine information about the country's nuclear program as a whole; (2) it also allows step-by-step assessment of the proliferation route chosen by the country and the current stage of development of this route.

*VI.E.2. Open-Source Information Credibility and Relevance Assessment Methodology*

One of the primary concerns associated with the open-source information investigations is questionable reliability of data sources. It is important to keep track of the information confidence in order to estimate the reliability of the final results and conclusions. The following procedure is proposed for the community of academics for open-source information credibility and relevance assessment.

During the investigation all found sources and information obtained from these sources would be assigned with two coefficients: relevance ($r_n$) and credibility ($c_n$). The coefficients would range between 0 and 1. The first coefficient would describe the relevance of the information or data analysis results to the subject of the investigation. For example, images of specific facilities or shipping data should have relevance coefficient of equal or close to 1. Historical/political background, which is usually not directly related to the particular proliferation activity, should have a less than 1 relevance coefficient. The credibility coefficient provides a numerical description for the level of reliability for the sources used. For example, most of the historical data will have credibility equal or close to 1 and some of the local press reports or watchdog group revelations may have a less than 1 credibility coefficient.

During the final data compilation and publishing the overall quality of the collected information should be assessed. This evaluation would help to estimate the credibility and reliability of the collection of information from open sources and data analysis results for each block of the compilation. Data confidence index for each stage $i$ is given by

$$u_i = \frac{\sum_{n=1}^{N} c_n \cdot r_n}{N} \qquad (1).$$

If the population of sources used in compilation of data for a block within the investigation is large enough, the confidence index will be representing the true statistical mean. Often there would be sources in the population with one or both coefficients significantly lower than the rest of the population. Such outliers tend to significantly decrease the average. There are several approaches to defining these numbers and treating them. One of the methods is statistical analysis of the population and defining outliers as numbers that are outside of the three standard deviations range from the mean of the population.

Several options should be taken in consideration. If the population of sources has a wide span of credibility and relevance coefficients, the standard deviation of such a population would more than likely be high. In this case the range of two or even one standard deviation should be used for defining outliers. If standard deviation of the population is low, than standard “3-σ rule” should be applied. The standard deviation is given by

$$\sigma_i = \sqrt{\frac{\sum_{n=1}^{N}(x_n - \overline{x})^2}{(N-1)}} \qquad (2).$$

Once statistical outliers are selected, operator’s judgment should be used to determine actions towards them. Usually sources not directly related to the subject or sources with extremely low credibility are most likely to become outliers. In most cases, due to their insignificance, these sources can be excluded from the population. Another case is when one of the sources is providing information contradicting some the findings of the investigation. In this case information should not just blindly be excluded from the population but additional searches should be performed to verify information from other sources and investigation conclusions.

TABLE XIII

Example of Distribution of Credibility and Relevance Coefficients within Hypothetical Investigation Block

| Hypothetical Source | $n$ | $c_n$ | $r_n$ | $c_n \cdot r_n$ | Outlier (1σ) |
|---|---|---|---|---|---|
| Watchdog | 1 | 0.70 | 1.00 | 0.70 | |
| Historic Info | 2 | 1.00 | 0.20 | 0.20 | Yes |
| Historic Info | 3 | 1.00 | 0.50 | 0.50 | |
| Press Report | 4 | 0.90 | 0.90 | 0.81 | |
| Press Report | 5 | 0.10 | 0.20 | 0.02 | Yes |
| Watchdog | 6 | 0.95 | 1.00 | 0.95 | |
| Scientific Article | 7 | 0.99 | 1.00 | 0.99 | |
| Scientific Article | 8 | 1.00 | 0.80 | 0.80 | |
| Watchdog | 9 | 0.82 | 1.00 | 0.82 | |
| Satellite Image | 10 | 1.00 | 1.00 | 1.00 | |
| Visual Imagery Analysis | 11 | 0.94 | 1.00 | 0.94 | |
| Multispectral Imagery Analysis | 12 | 0.92 | 1.00 | 0.92 | |
| Transit Company Info | 13 | 0.01 | 1.00 | 0.01 | Yes |
| Transit Company Info | 14 | 0.70 | 1.00 | 0.70 | |
| Middleman Info | 15 | 0.84 | 1.00 | 0.84 | |
| Shipping Paperwork | 16 | 0.57 | 1.00 | 0.57 | |
| Shipping Paperwork | 17 | 0.88 | 1.00 | 0.88 | |
| Data Analysis Results | 18 | 0.75 | 1.00 | 0.75 | |
| Contradictory News Report | 19 | 0.60 | 0.01 | 0.005 | Yes |
| Other | 20 | 0.91 | 1.00 | 0.91 | |
| | | $u_i$ | | 0.6639 | |
| | | Std. Deviation | | 0.3390 | |

An example of a hypothetical population of open sources of information is presented in Table XIII. A variety of sources and data analysis results related to one of the blocks of an investigation were collected. Each of the sources was assigned credibility and relevance coefficients. Based on assigned values, the data confidence index ($u_i$=$0.6639$) and standard deviation ($\sigma_i$=$0.3390$) were calculated. Because the standard deviation in this case was high, a "1-σ rule" was used for outlier analysis. Four potential outliers were defined. After review of the data the following actions were proposed:

a. Keep historical information documentation (*n=2*) in the population. Even though it has low relevance to the block *i*, it provides valuable historic background to the overall investigation;

b. Remove press report (*n=5*) from the population since, it has very low credibility (*0.10*) and also low relevance to the block *i*. Removing this source will not impact results significantly, but it will increase the overall data credibility index;

c. Remove the source (*n=13*) containing information about the company used for transit of materials or technology into the country. Credibility of this source is too low (*0.01*);

d. Keep the news report (*n=19*) contradicting conclusions of the investigation and perform addition information search. Based on the new results, this report would be removed or investigation conclusions will be changed.

After following the recommendations above, new confidence index value became 0.74 and standard deviation is 0.27. If, after additional information search, it would be determined that contradictory news report can be removed from the population, the values would become 0.79 and 0.2 respectively.

*VI.E.3. Figure of Merit*

During an open-source investigation, besides estimating data confidence index for each individual block, it is important to evaluate the results of the investigation as a whole. It is also important to have some numerical value describing the suspect country's progress in acquiring a nuclear weapon. A single number (figure of merit – FOM) characterizing both the country's progress and the quality of information used to analyze this progress is proposed for use by a community of academics.

The following procedure is suggested for calculating the FOM. During the investigation, information collected in each individual block and conclusions made based on this information would be assessed and two indexes would be assigned to every block. The calculation procedure for the first, data confidence index ($u_i$), was described in the previous section. The second, progress index ($w_i$), would not have any calculation method and would be assigned by analysts based on the information collected. This index would describe estimated progress of a country in completing a particular stage of the nuclear fuel cycle. An example of a hypothetical investigation thread consisting of seven steps and the distribution of confidence and progress indexes is presented in Fig. 30.

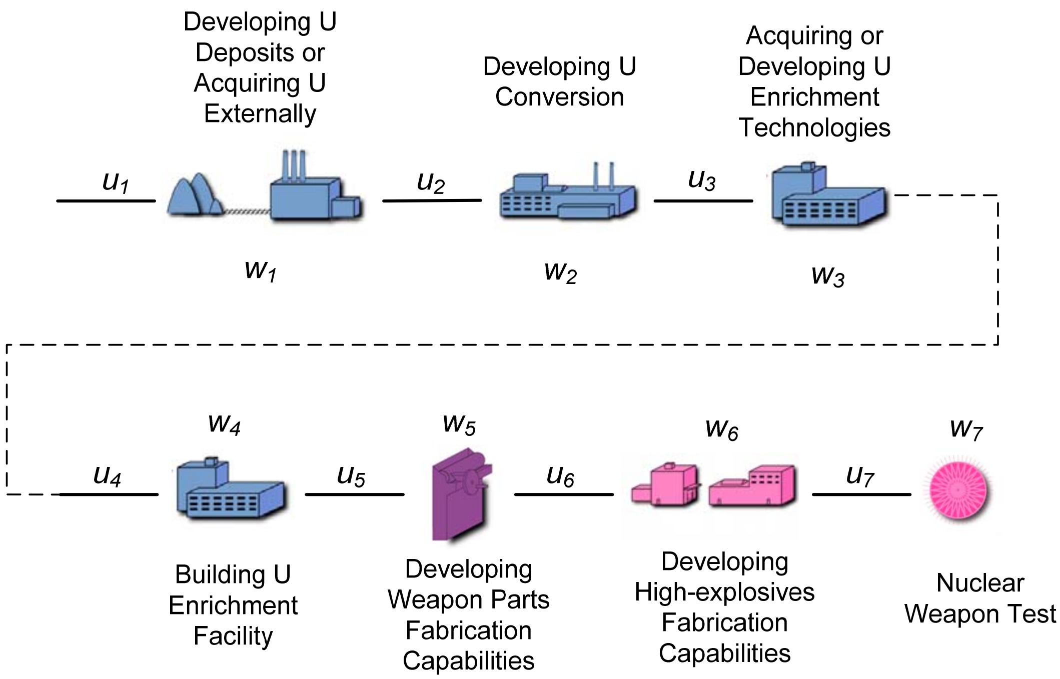


Fig. 30. Distribution of Confidence and Progress Indexes in Investigation Thread.

For any full investigation or a particular part of it FOM is given by

$$FOM = \prod_{i=1}^{I} (1 + u_i \cdot w_i) \cdot \frac{1}{2^I} \tag{3}$$

where $u_i$- confidence index for a block $i$ of the thread,

$w_i$ -estimated progress index for a step $i$ of the nuclear fuel cycle,

$I$ – total number of blocks in the investigation or the number of blocks being assessed.

FOM is a number between 0 and 1 that provides a quality assessment of the results of investigation. The closer this number to 1 the higher probability of the country of interest completing its nuclear program or a part of it being assessed, with the confidence provided by information collected as a part of the investigation.

An example of an investigation thread with hypothetical confidence and progress indexes is presented in Fig. 31. In this example, according to investigators of individual blocks, the country had completed developing uranium ores (or obtained some raw material from another nation), had developed uranium conversion capabilities, and acquired necessary technologies for uranium enrichment. Also it has completed building about 75% of its own enrichment facility. No weapons part or high-explosives development were started at the time of investigation.

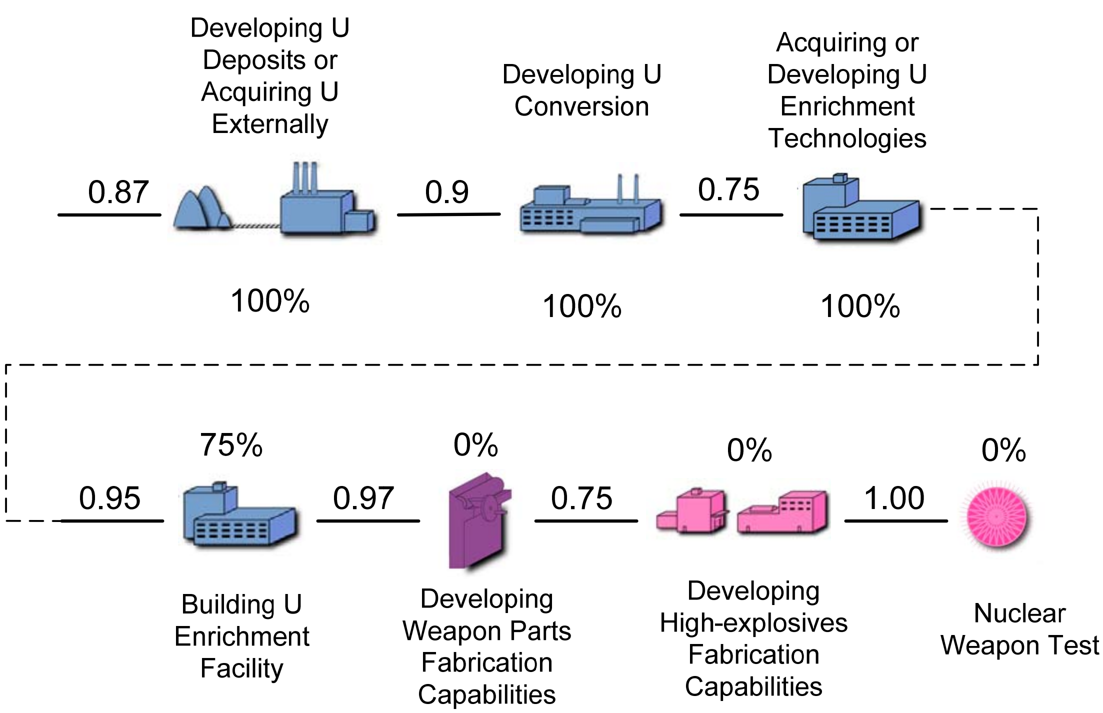


Fig. 31. Example of an Investigation Scenario with Hypothetical Confidence and Progress Indexes.

Based on the data confidence and progress estimates for each individual block, a series of FOM's for the entire program and progressive steps can be calculated. The results are summarized in the Table XIV. As expected from the chart, the overall nuclear weapons program of the country has a very low FOM (0.08). The country under investigation has not completed its uranium enrichment facility and has not started any preparation for building an actual weapon. On the other hand, the country of interest made substantial progress in building its uranium enrichment program: 0.67 for the steps 1 through 4.

TABLE XIV

FOM Calculation Results of the Hypothetical Case Investigation

| **Stage** | **FOM** |
|---|---|
| 1 | 0.94 |
| 2 | 0.89 |
| 3 | 0.78 |
| 4 | 0.67 |
| 5 | 0.33 |
| 6 | 0.17 |
| 7 | 0.08 |
| Full | 0.08 |

Perhaps, more representative is a graph describing the hypothetical country's achievements in creating a nuclear program (Fig. 32). A threshold can be established, and all steps above the threshold would be considered to have significant progress. Ideally the full curve should be located above the threshold for the program to become military significant.

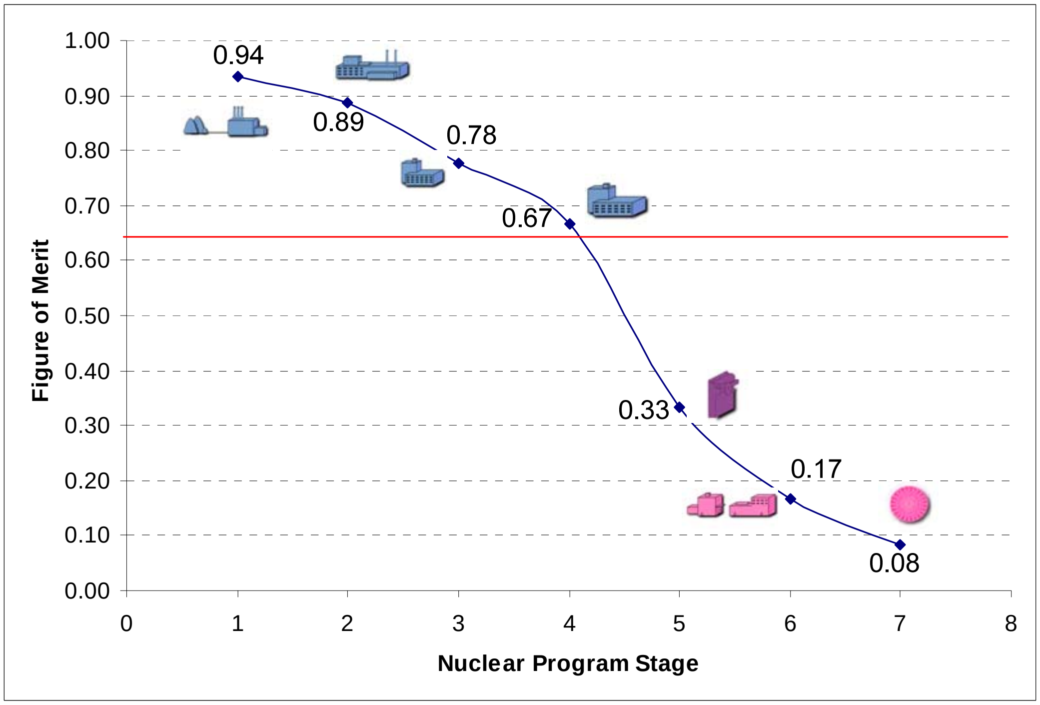


Fig. 32. FOM for Different Stages of the Hypothetical Nuclear Weapons Program.

## VI.D. Conclusions

Open-source analysis is a complex task that requires a large amount of time and resources. This type of analysis is becoming more recognized by various treaty verification organizations including the IAEA. An international community of academics would be one of the means of providing necessary manpower and expertise to aid the IAEA in searching for undeclared nuclear activities around the world. Creating such a community would help to unite and organize a large number of researchers, professors, students and other representatives of academia from all over the world. But the more important task is to create an effective structure and to provide the mechanism for the members of the community to interact, communicate, collaborate, teach, learn, exchange experience and so on. Only with such effective structure verification and monitoring can proliferation detection tasks be performed and successfully completed.

# CHAPTER VII

# LIMITATIONS AND PROLIFERATOR'S POTENTIAL SPOOFING TECHNIQUES AND SCENARIOS

## VII.A. Introduction

Use of various individual open sources of information and their combinations for tracking nuclear nonproliferation regime violations appears to be a powerful tool, but there are some limitations associated with these sources. Besides, potential proliferator, being aware of constant monitoring, may use some tricks to hide illegal activities or mislead investigators. This chapter explores potential weaknesses of all information sources described in previous chapters. Also several, so-called spoofing techniques, and tricks that may be used by a potential proliferator in order to avoid being caught, are investigated.

## VII.B. Commercial Satellite Imagery

Several limitations for detection of undeclared facilities are imposed by the nature of satellite imagery itself. Limited spatial and spectral resolutions, high prices, the size of Earth, satellite return timeframe, etc. are the main contributors to overall restrictions imposed by use of satellite imagery. In addition there are several limitation associated with imagery analysis algorithms, such as limited precision of classification, time consuming ROI selection and performance tuning, etc.

*Limited spatial resolution*. During the recent decades spatial resolution of commercially available satellite imagery has improved dramatically and currently panchromatic imagery of up to 0.6 m resolution is available on the market. This level of detail may not always be sufficient for comprehensive analysis of covert facilities. At the same time as imagery resolution was improving new technologies were developed allowing using small-scale facilities that can produce enough material for one or two weapons a years rather than constructing a full-scale industrial size plant. It is more likely that a "smart" proliferator would follow this route. In case of an underground facility or even a reactor confinement building, more detailed imagery would help to analyze individual visible features (piping, wall thicknesses, etc.) in order to have better estimate of facility designation and scale.

*Limited spectral resolution*. As it was shown in Chapter III very often having four spectral bands specific to multispectral imagery is not enough for 100% accurate detection and separation of various materials of interest on a scene. One of the solutions to this problem is utilization of hyperspectral imagery that has hundreds of narrow bands. Bigger number of bands provides a much better quality of spectral signatures, but this type of imagery has much lower spatial resolution than multispectral imagery. Besides, there are only few commercial sensors available and it is more expensive than other imagery types.

*High prices*. Although prices of satellite imagery are constantly going down, significant budget is required in order to maintain a comprehensive library of imagery for various regions all over the world. This would be especially pressing for organizations with limited resources like the IAEA, or academic societies like INMAC. As it was shown earlier in most cases additional types of data like multispectral, hyperspectral, radar or infrared are needed besides high-resolution images. These types of imagery are usually even more costly and increase the financial burden on research organizations. Another consideration should be when a country of interest is watched in progress (construction stages of a suspicious facility), then several images of the same place over the timeline would be needed and in some cases a special pass of a satellite over the place of interest has to be ordered. Maintaining an up-to-date and high quality imagery library can become a significant part of a monitoring organization's budget.

*Visual signatures*. Some of the nuclear fuel cycle facilities do not have distinct visual signatures that can be used for their identification. For example, there are no observables that would indicate the value of satellite imagery for the purpose of identification of undeclared fuel fabrication activities. Moreover, significant indicators would be unlikely even during construction of these facilities. Another example: one of the pitfalls of the gas centrifuge enrichment method is that a medium-sized warehouse or building can house a sufficient number of gas centrifuge cascades to produce one or more nuclear warheads per year. This makes uncovering enrichment facilities of potential proliferators more difficult. Unlike gaseous diffusion enrichment facilities, or even nuclear reactors that can produce plutonium, a typical gas centrifuge enrichment facility would not require the cooling or electrical systems that are readily visible in other types of enrichment facilities.

*Spoofing techniques*. There is a number of techniques that a potential proliferator may use to avoid detection. Commercial satellite imagery is available to everybody including potential proliferators. Knowing investigators capabilities and using those capabilities themselves, a state or organization constructing a covert facility, may develop several methods to try to avoid detection.

1. **Underground facilities**. In order to hide signatures specific to nuclear fuel cycle facilities, a proliferator may choose to construct and underground facility. Only a few necessary infrastructures will appear on the surface of the ground. Another consideration for underground construction is a robust protection from air strikes. Detection of underground facilities is still possible during the construction phase.
2. **Inside hill or mountain facilities**. In order to avoid detection of underground facility during the construction phase, a proliferator may choose to build a facility inside a hill or a mountain to mask the project as a mining operation. This type of construction will also provide a stronger air strike protection. As a disadvantage of such type of construction for the proliferator is an extremely high cost which, combined with combined with an average cost of nuclear fuel cycle facility, makes the total construction cost almost astronomical and affordable only to very reach states.
3. **Overcast skies and dark time of a day**. Another trick that can be used to hide some illegal activities and truck or train movements is using overcast

skies and nighttime. In this case the only option for investigators is expensive radar and infrared thermal imagery.

4. **Camouflage**. Camouflage technologies may be used to hide parts of infrastructure from being visible from space. Besides facility infrastructures usually means of protection, like antiaircraft guns, that may look suspicious around facility are camouflaged. In this case investigators should use multispectral or hyperspectral imagery for scene material analysis.
5. **Constructing confinement/containment buildings similar to civilian industrial facilities**. Potential proliferator may choose to build a facility that looks similar to one of the civilian type factories, for example chemical plants. If carefully thought through, this trick may mislead investigators.
6. **Proximity to large civilian plants**. Contrary to a trend of constructing covert facilities in distant non-populated areas, a proliferator may choose a location with a proximity to a large civilian plant. This type of location will allow a newly constructed covert facility to look like a part of civil industry and not raise suspicions.

This list consists of just a few examples of spoofing techniques that may be used by nuclear nonproliferation regime violators in order to hide their illegal covert facilities.

*VII.B.1. Iran's Natanz Underground Uranium Enrichment Facility as an Example of an Attempt to Create an Undetectable Covert Facility*

One of the classic examples of a covert facility is the uranium enrichment centrifuge plant in Natanz, Iran. An original centrifuge plant was built above the ground and contained experimental centrifuge cascades for testing, research and personnel training. The second, newer, part of Natanz facility was created under ground, and recently after completion of "secret" centrifuge halls, was covered with dirt. The underground structure had raised a lot of questions and concerns. In response to these questions and concerns the Iranian Government issued a number of statements about the purpose of this facility. One of the first statements even described it as an agricultural facility. According to some sources there were also some plans to plant trees above the underground halls to mask them even more.

Satellite imagery allows analyzing some of the spoofing techniques used by the creators of the plant along with several distinct signatures that can be used by investigators. One the recent satellite images of the facility from the Google Earth database is presented in Fig. 33. The only objects visible to an analyst on this image are: several medium size industrial buildings accompanied by an administrative complex (original centrifuge plant), security fence around them, piles of dirt and dump trucks outside the fence. More than likely without thorough analysis an analyst may decide that this plant is one of the civilian industrial facilities and continue the search. Another possible case is, if imagery analyst would be able to determine that buildings in the image belong to a centrifuge uranium enrichment plant, the capacity of this plant would be significantly underestimated.

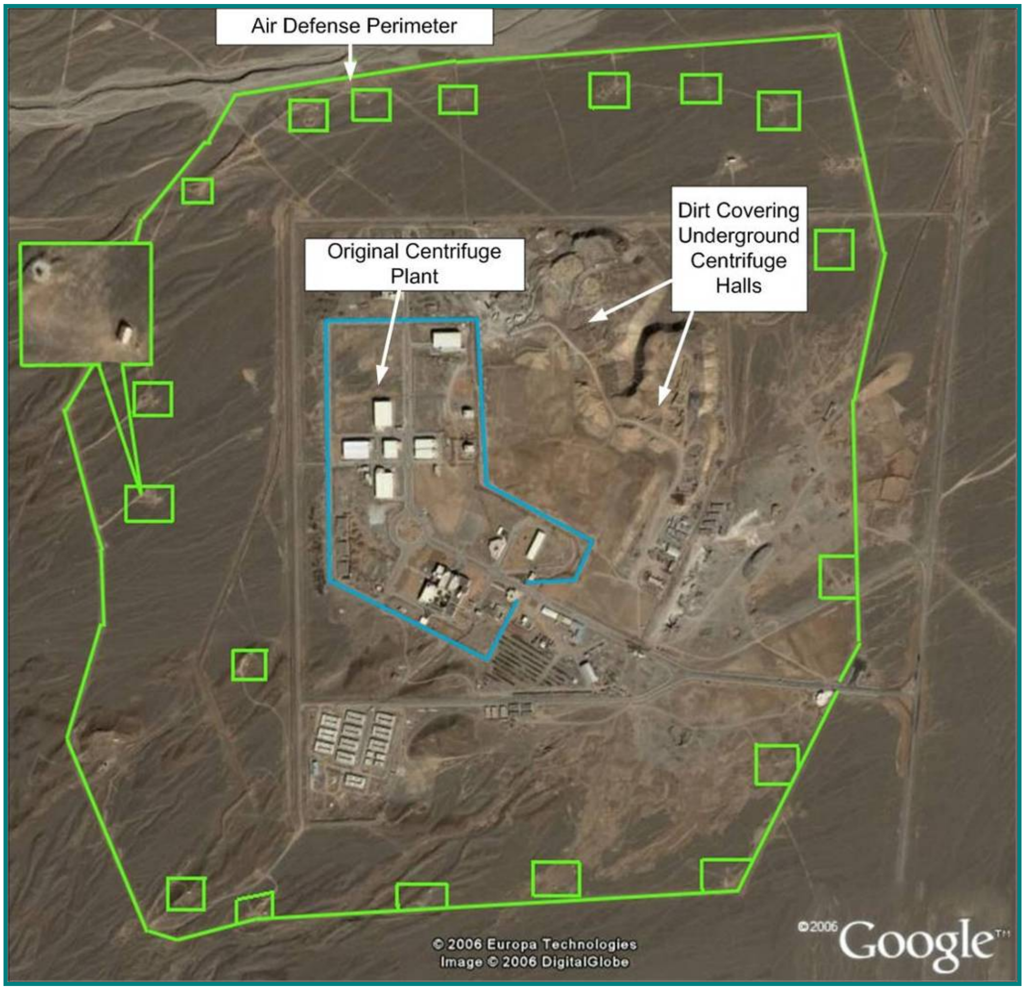


Fig. 33. Iran's Underground Uranium Enrichment Centrifuge Facility in Natanz.

On the other hand there are several elements on this image that could provide evidence of a clandestine facility. These features should rise suspicion and result in more thorough investigation of the facility and its surroundings, including obtaining archived imagery to analyze various construction phases. One of these signatures is a secluded remote location of this plant. Another is a set of antiaircraft guns forming an air defense perimeter. These guns are not readily visible on the image and can only be found after careful inspection of the plants surroundings. Large area next to the plant being covered with dirt could also raise some questions about the purpose of this facility.

Iran's uranium enrichment facility in Natanz is one of the spectacular examples of a covert facility. It is also an example of successful uncovering of a clandestine program. The intention for this plant was to create a large facility with only a few small buildings above the ground. Underground allocation would not only help to hide the real purpose and scale of the facility, but also would protect equipment from potential air strikes by thick layers of concrete and dirt. After the discovery of this plant, multiple images from different construction stages were studied that allowed assessing inside configuration of the underground part of the facility.

## VII.C. International Customs Documentation

There are two main limitations associated with the use of customs data for tracking nonproliferation regime violations around the world: tremendous amount of data and limited access to documentation. Millions of shipments of various materials and machinery take place every day. Each transaction is registered in shipper's, recipient's, and all transition country's databases. Copies of all shipping paperwork are also stored in these databases. Tremendous amount of data generated over time poses a problem of creating a suitable and fast search engine that would allow information extraction in a timely manner.

Another potential problem might be in acquiring access to the data. Theoretically and organization like INMAC can request access to the database of a country that is suspected to be involved in shipment of illegal materials. In reality information owner may decline the request or provide only a limited access to the database. This scenario is likely to happen when only several outcast countries are involved in a transaction.

There are also a number of spoofing techniques that can be used by proliferator to hide real intentions and mislead investigators. For example Iraq had established different "procurement channels" within its nuclear weapons program. The goal of these channels was to avoid attracting attention to the large quantities of materials and equipment the government needed for nuclear weapons projects, and to tailor the proposed channel to the type of item needed. Iraq's central procurement office often divided a project's list of desired items into different lists comprised of items taken from several distinct project lists. In this way, the resulting lists of equipment would not have any resemblance to the original lists. Thus, the final lists would be less likely to raise suspicions among foreign intelligence agencies, which can spend a considerable effort in analyzing exports looking for patterns suggesting secret technical nuclear projects [85].

### VII.D. Press Reports

Press reports have several major disadvantages as a resource for open-source investigation. First, similarly to the customs data, it is a tremendous amount of information. Special search engine is needed for effective browsing and selection of related to the subject of investigation reports. Second is limited access to newspaper and news releases archives. Although currently more and more newspapers are becoming available online, it is still more exclusive to developed democratic states. Also usually only state's central or federal news agencies publish their material on the internet. Small local newspapers, which in many cases become a more valuable resource, can only be found in paper in the area of origin.

There are several ways a potential proliferator may use press reports for the purposes of misleading investigators. Fake news announcement or press release is the most possible spoofing technique. For example, when a construction of a new facility starts a press release would announce that it is a new chemical plant for fertilizer production, when it is, in fact, a uranium conversion plant.

### VII.E. CTBT Network Data

Currently the main disadvantage of CTBT Network data is that it is not available to general public. If it was accessible, the "resolution" (the average distance between adjacent monitoring stations) of the network might not always be sufficient for the purposes of investigation. CTBT Network was originally designed to detect nuclear explosions, when a significant amount of radioactive fission products would be released into the atmosphere. In case of a small-scale nuclear facility radioactive material release concentrations might be too small, or the closest monitoring station might too far, for detection to take place.

### VII.F. Conclusions

As new methods of detection and monitoring are being developed, new tricks and spoofing technologies will also be developed by proliferators. It is very important for investigation organizations, like INMAC, to consider and determine potential spoofing techniques. One way is to investigate methods currently used by violators. Another, and probably the most effective one, is for investigators to think what they would do if they were proliferators. Knowing investigation resources, it is possible to come up with a number of things that a real proliferator would consider. Then generated ideas should be analyzed and, if possible, methods of detection should be developed.

# CHAPTER VIII

# CONCLUSIONS

The main goal of this project was to prove the feasibility of formation of an International Nonproliferation Monitoring Academic Community (INMAC). This community would utilize all publicly and commercially available sources of information for the purpose of detecting covert facilities and activities intended for the unlawful acquisition of fissile material or production of nuclear weapons. Ultimately formation of such organization would provide necessary aid and resources to the IAEA and would strengthen the international nuclear nonproliferation regime as a whole.

The availability and use of commercial satellite imagery systems, commercial computer codes for satellite imagery analysis, CTBT verification International Monitoring System, publicly available information sources such as watchdog groups, press reports, scientific and technical literature, and Custom Services information were explored. The results proved that publicly and commercially available sources of information and data analysis can be a powerful tool in tracking violations in the international nuclear nonproliferation regime. It was also shown that the best result can be achieved by integrating information from all available sources.

During the satellite imagery analysis study panchromatic and multispectral images of several known and unknown nuclear installations were investigated. A set of signatures specific to various nuclear fuel cycle facilities was defined. These features allow distinguishing nuclear installations from other types of industrial facilities. In addition to the facility type, applicability of satellite imagery for determination of specific characteristics, such as production capacity or electric power consumption, was explored. Investigation of a blind case scenario proved the applicability of defined visual signatures for detection and characterization of the nuclear installations.

Open-source investigation of the Libyan nuclear weapons program and its attempts to acquire uranium centrifuge technology was described. The level of detail of information compiled from the full variety of publicly available sources of information serves as another proof for the viability of members of academia performing open-source investigation for nonproliferation regime monitoring.

Successful formation and operation of an international community of academics requires an effective mechanism of interaction and information exchange between the members of the community. As a part of this research project the structure for INMAC was proposed. A framework for the open-source investigation, interaction between various research groups within the community, and integration of data from the wide variety of publicly and commercially available sources of information was created. Also, the means for controlling data confidence and estimating country's progress in developing a covert nuclear weapons program were selected.

The last part of this work involved exploring various methods and techniques that can be used by a potential proliferator to avoid detection of a secret weapons program. Identifying the weaknesses of open-source monitoring of nonproliferation regime would help in selecting new research areas that would stimulate development of new verification and data search techniques and ultimately improve the "open-source intelligence". The majority of these research projects can be carried out within the proposed community of academics.

The future work on this project would include an expanded study of commercial satellite imagery. This study would explore the integration of analysis results of all available remote sensor technologies: panchromatic, multispectral, hyperspectral, thermal and radar. Also, new image recognition techniques together with innovative methods of indexing and retrieving high-resolution image regions in large geospatial data libraries should be explored.

Another part of the future research would be in performing an open-source investigation of a well-known case only with the help of the publicly available sources that were available before a certain date (for example, the date of public announcement of the covert program). This type of investigation would help in identifying the amount of information that was available and what could be compiled before clandestine activities were officially revealed to the public.

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# APPENDIX A

# FULL SCENE CLASSIFICATION RESULTS

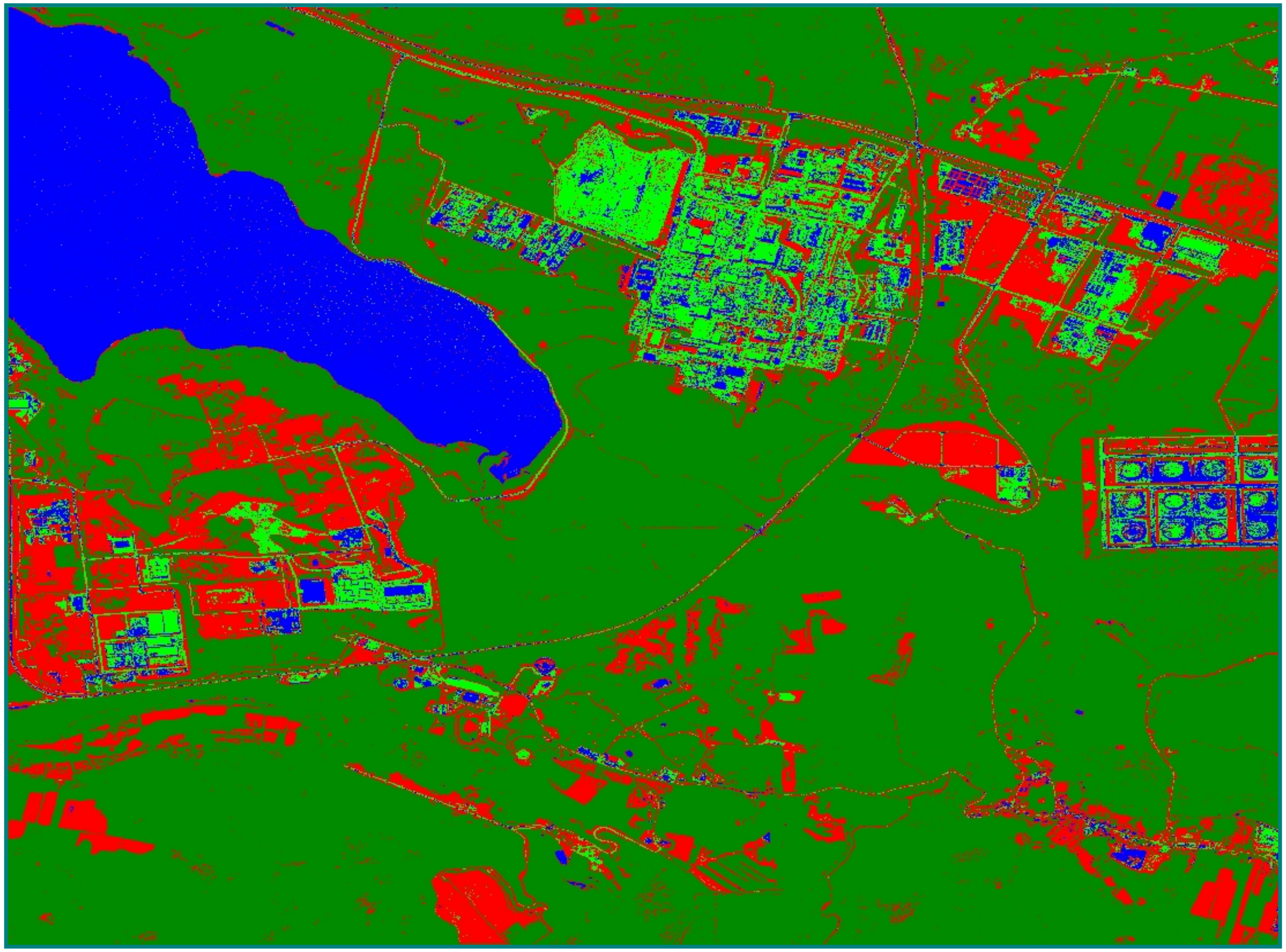

Fig. A-1. Full Scene: Gramm-Schmidt Sharpening, Bilinear/Average Resampling, Binary Encoding Classification (FGBABO00.img).

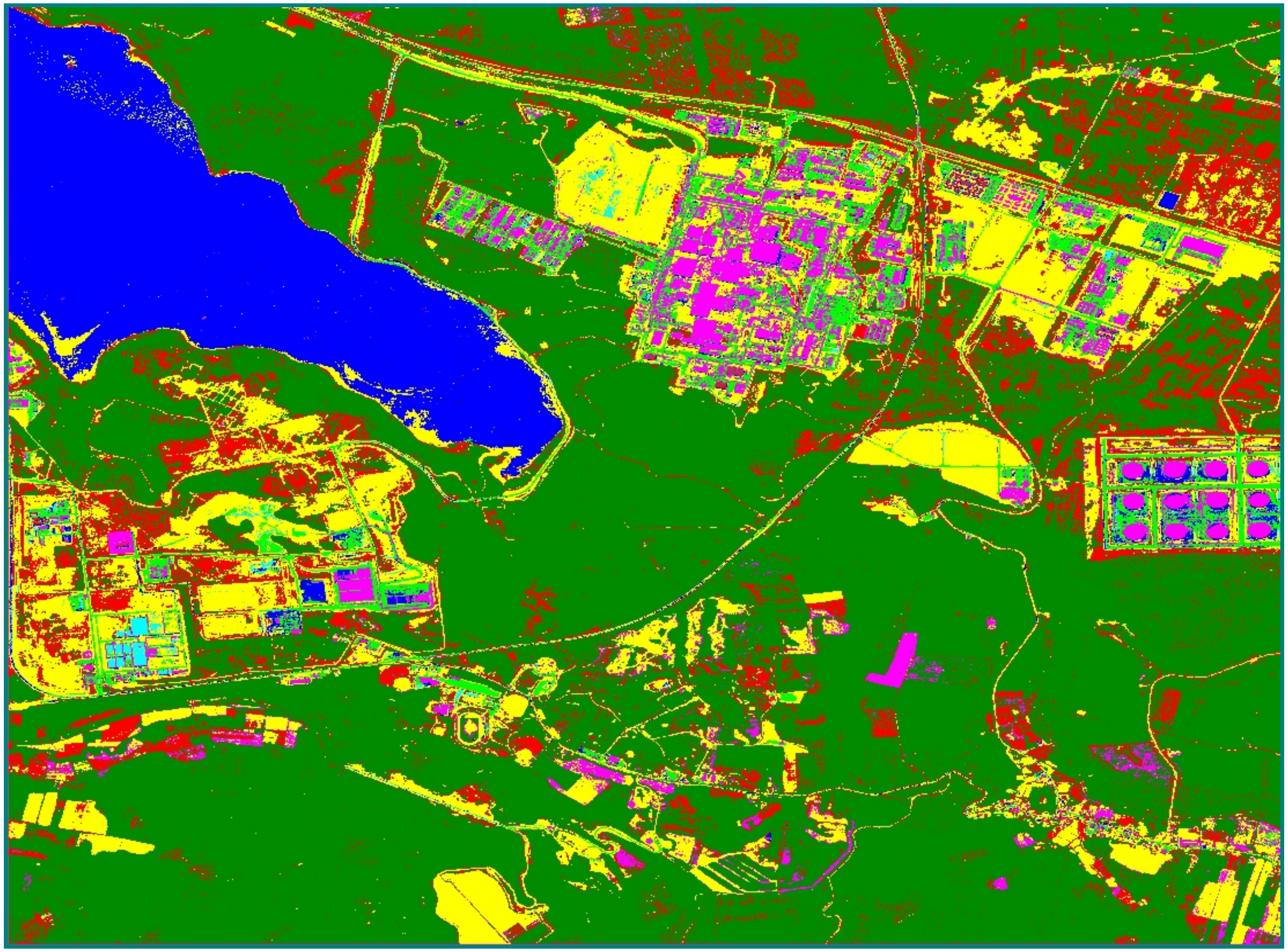

Fig. A-2. Full Scene: Gramm-Schmidt Sharpening, Bilinear/Average Resampling, Maximum Likelihood Classification (FGBALO00.img).

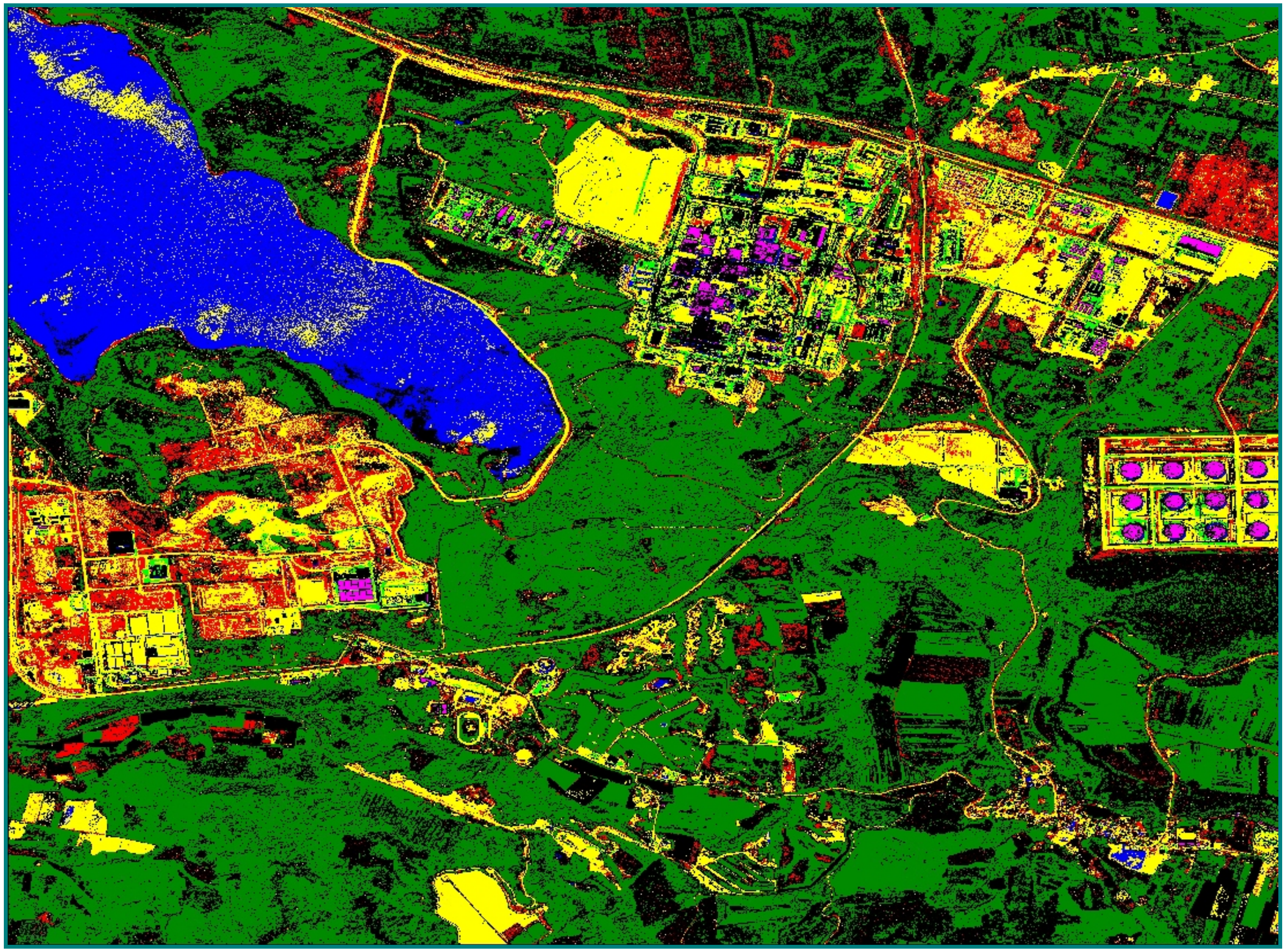

Fig. A-3. Full Scene: Gramm-Schmidt Sharpening, Bilinear/Average Resampling, Parallelepiped Classification (FGBAPO00.img).

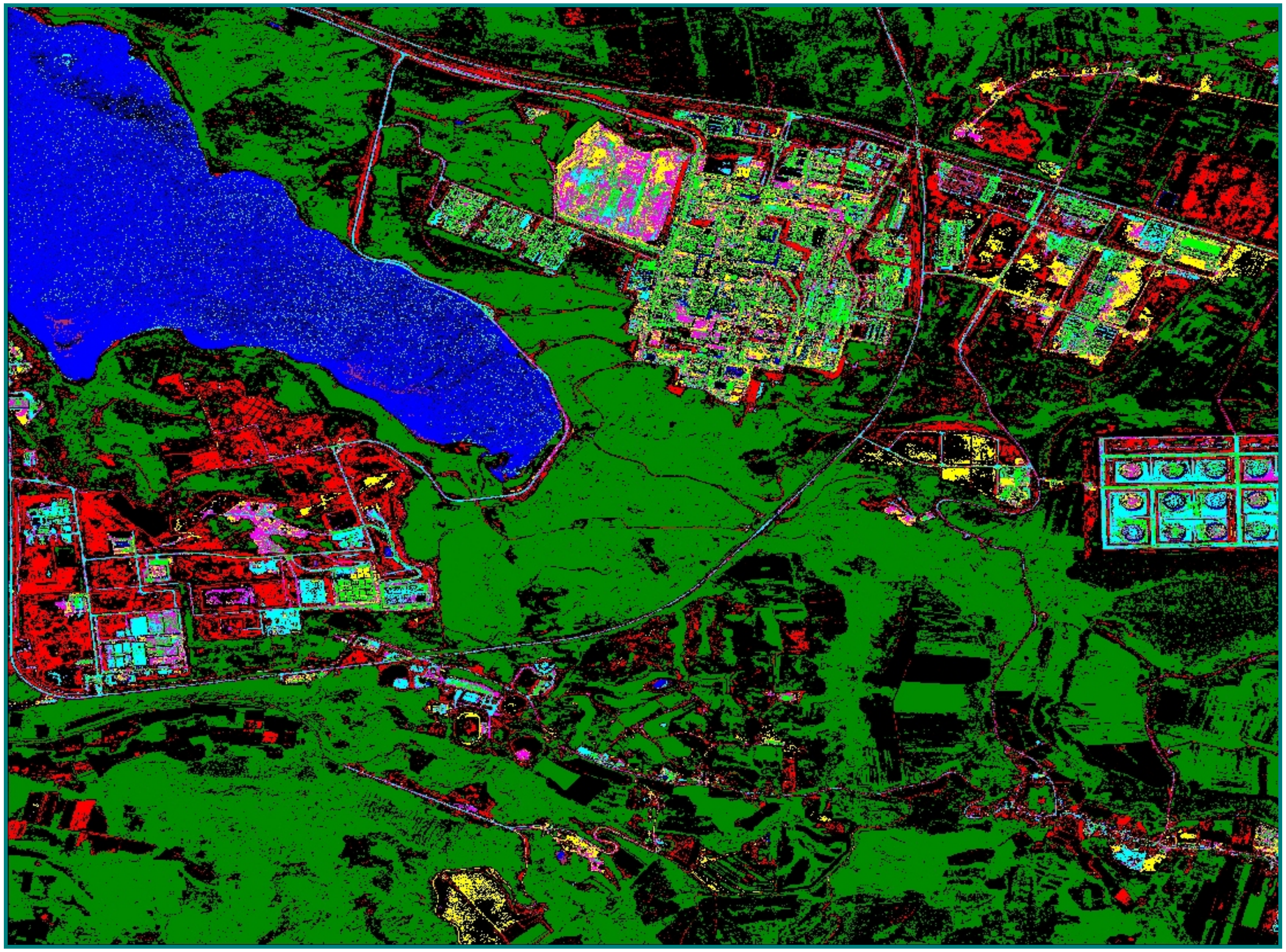

Fig. A-4. Full Scene: Gramm-Schmidt Sharpening, Bilinear/Average Resampling, Spectral Angle Mapper Classification (FGBASO00.img).

Fig. A-5. Full Scene: Gramm-Schmidt Sharpening, Bilinear/Sensor Resampling, Parallelepiped Classification (FGBSPO00.img).

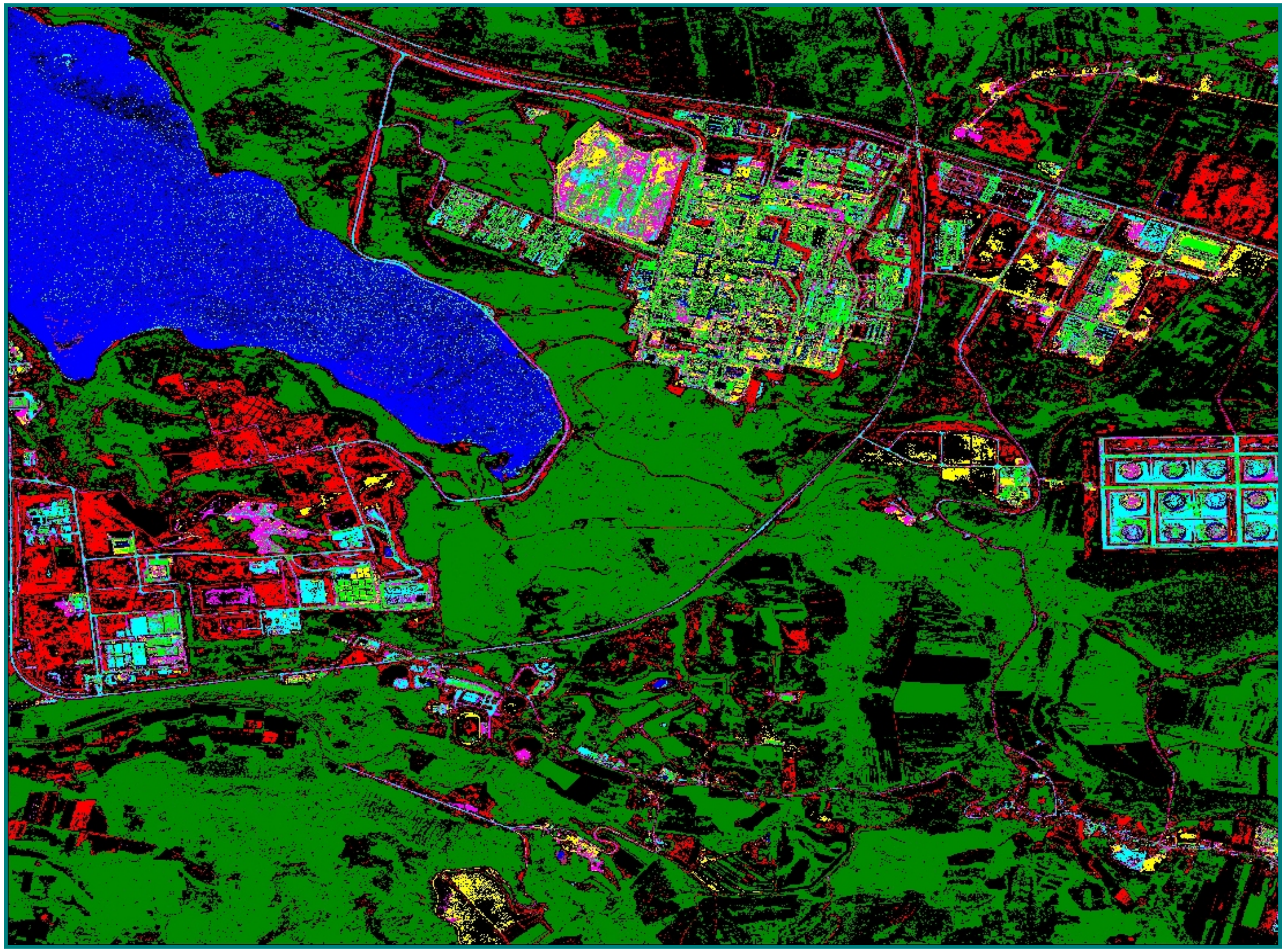

Fig. A-6. Full Scene: Gramm-Schmidt Sharpening, Bilinear/Sensor Resampling, Spectral Angle Mapper Classification (FGBSSO00.img).

Fig. A-7. Full Scene: Gramm-Schmidt Sharpening, Cubic Convolution/Average Resampling, Parallelepiped Classification (FGCAPO00.img).

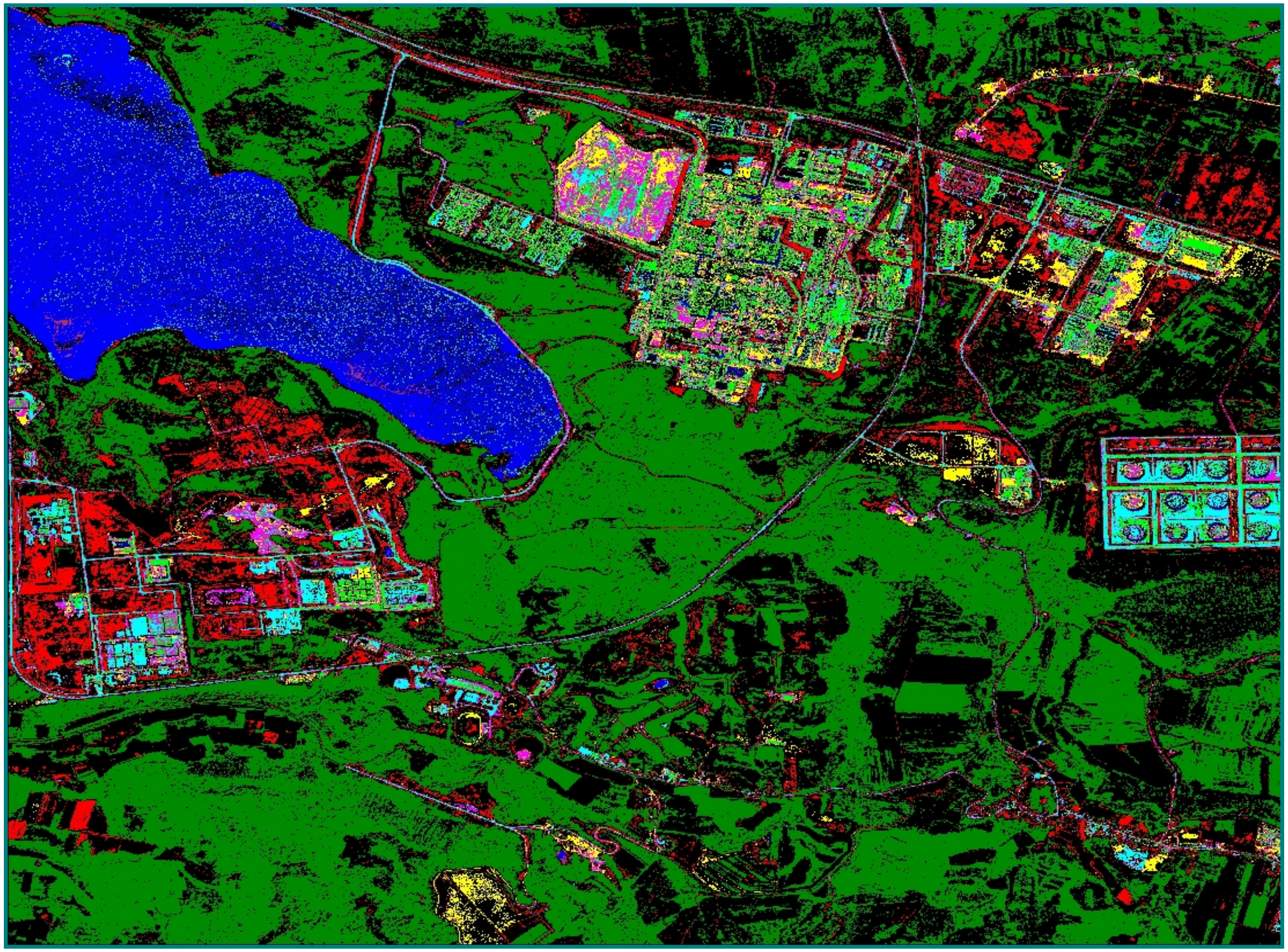

Fig. A-8. Full Scene: Gramm-Schmidt Sharpening, Cubic Convolution/Average Resampling, Spectral Angle Mapper Classification (FGCASO00.img).

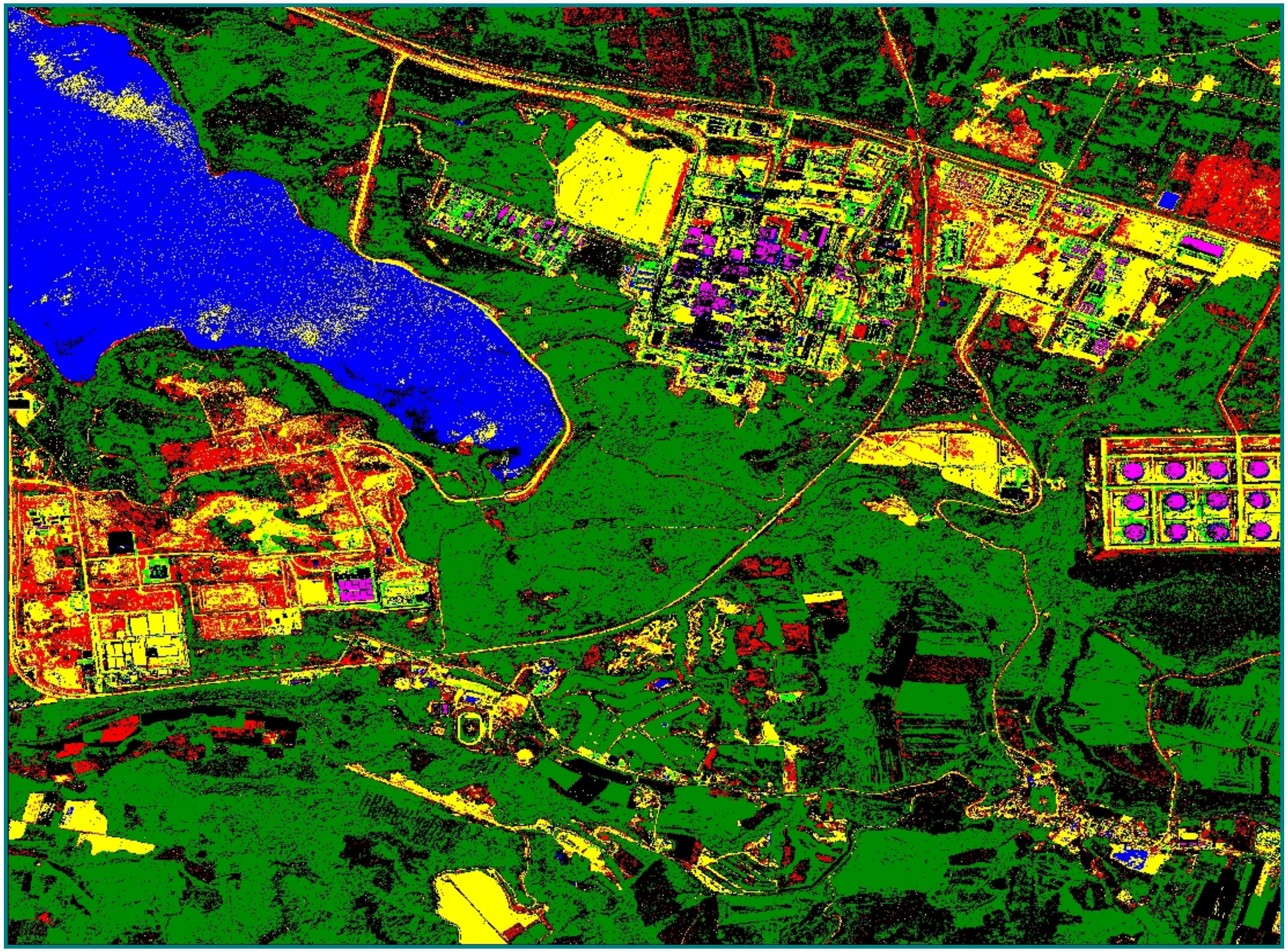

Fig. A-9. Full Scene: Gramm-Schmidt Sharpening, Cubic Convolution/Sensor Resampling, Parallelepiped Classification (FGCSPO00.img).

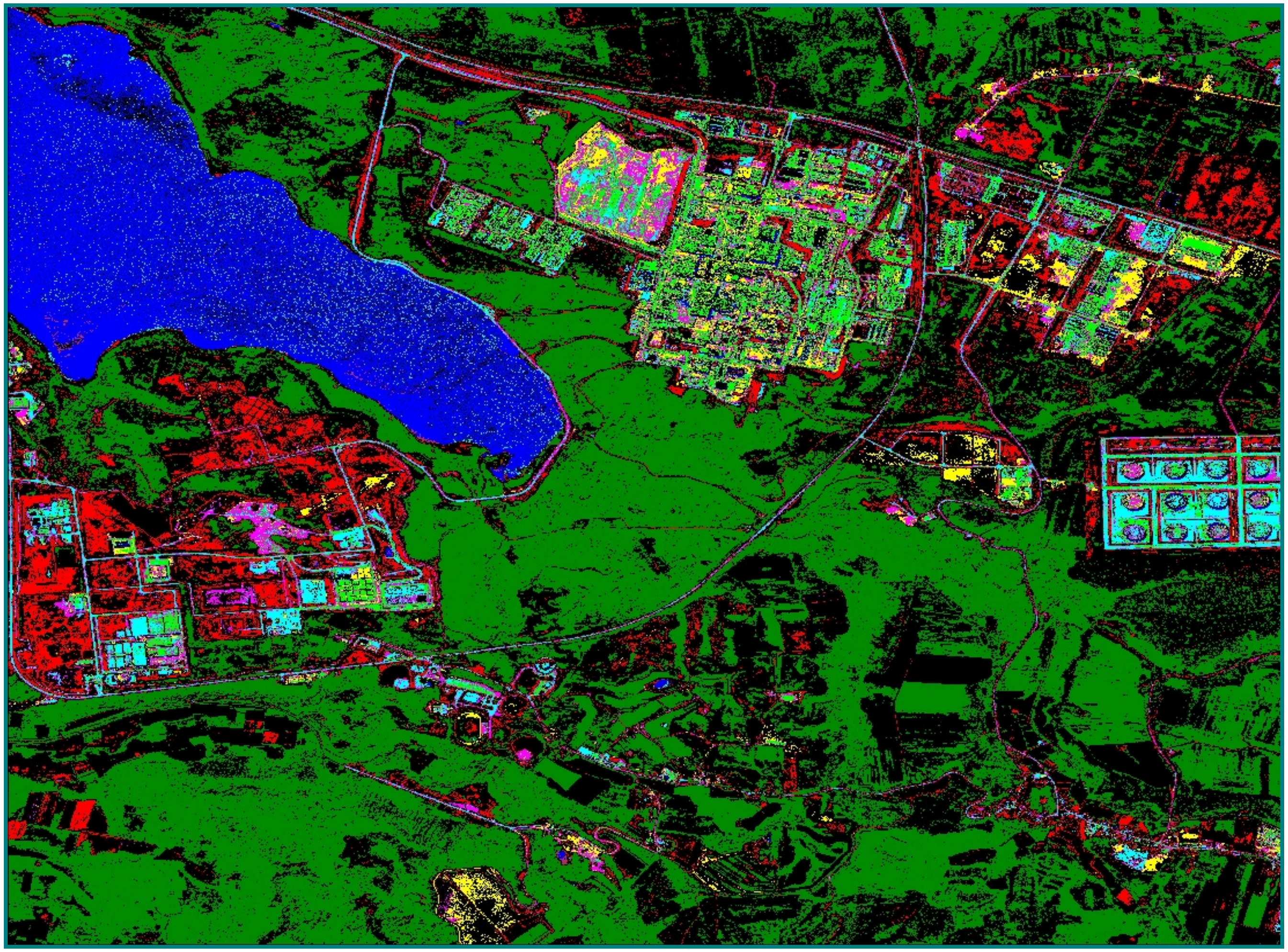

Fig. A-10. Full Scene: Gramm-Schmidt Sharpening, Cubic Convolution/Sensor Resampling, Spectral Angle Mapper Classification (FGCSSO00.img).

# APPENDIX B

# REPROCESSING PLANT CONSTRUCTION SITE CLASSIFICATION RESULTS

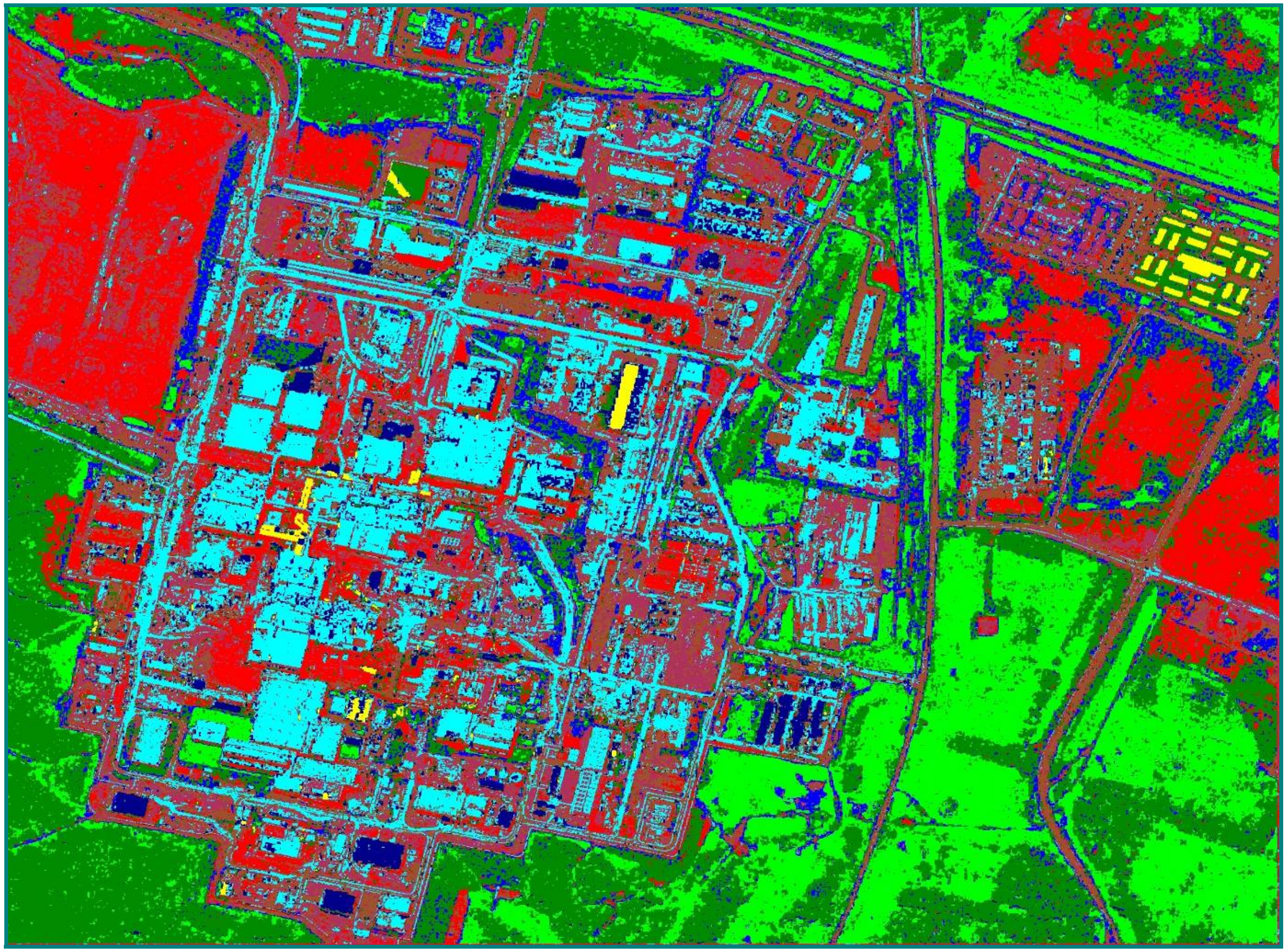

Fig. B-1. Reprocessing Plant: Gramm-Schmidt Sharpening, Bilinear/Average Resampling, Mahalanobis Distance Classification (RGBADO00.img).

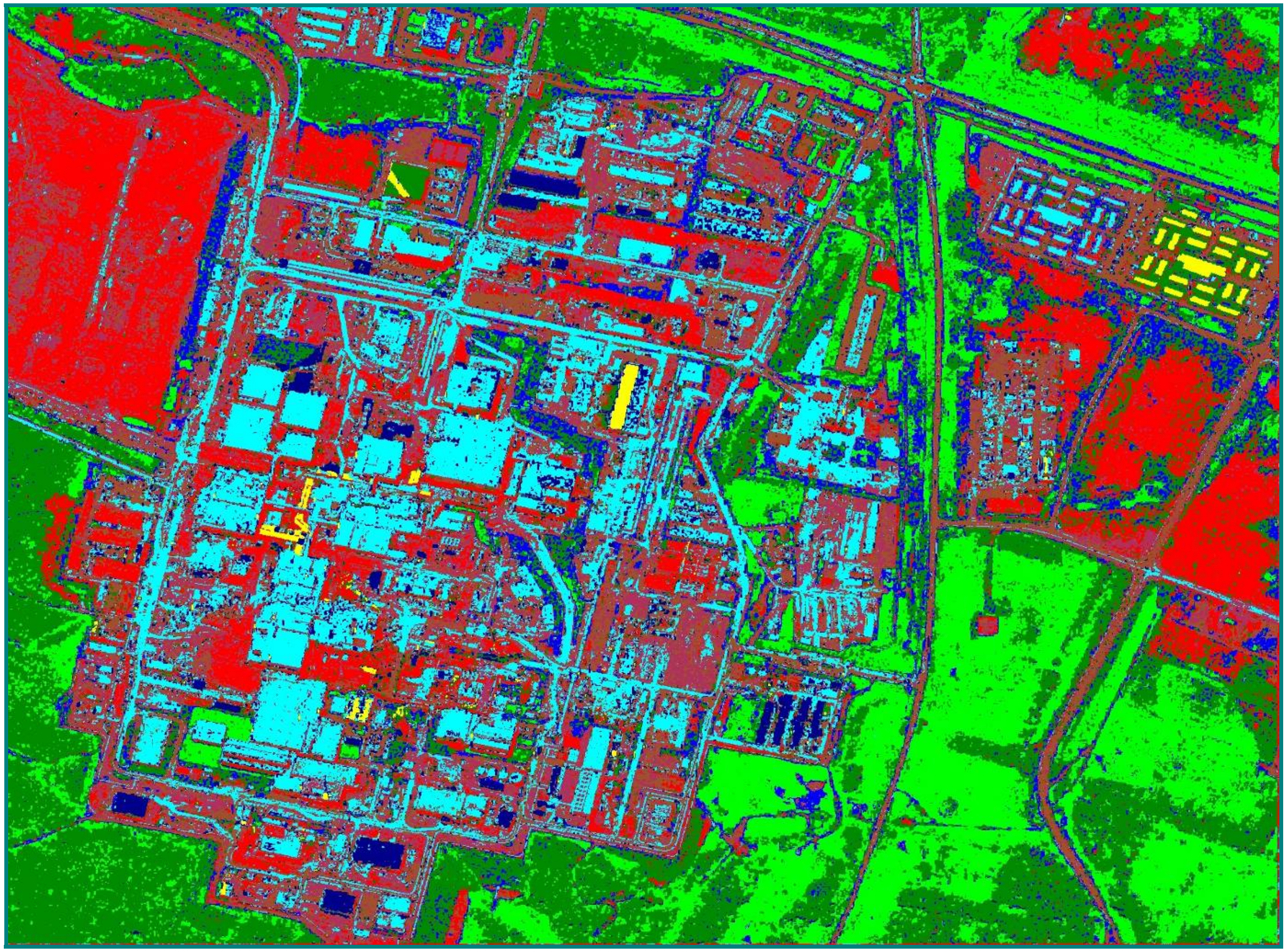

Fig. B-2. Reprocessing Plant: Gramm-Schmidt Sharpening, Cubic Convolution/Average Resampling, Mahalanobis Distance Classification (RGCADO00.img).

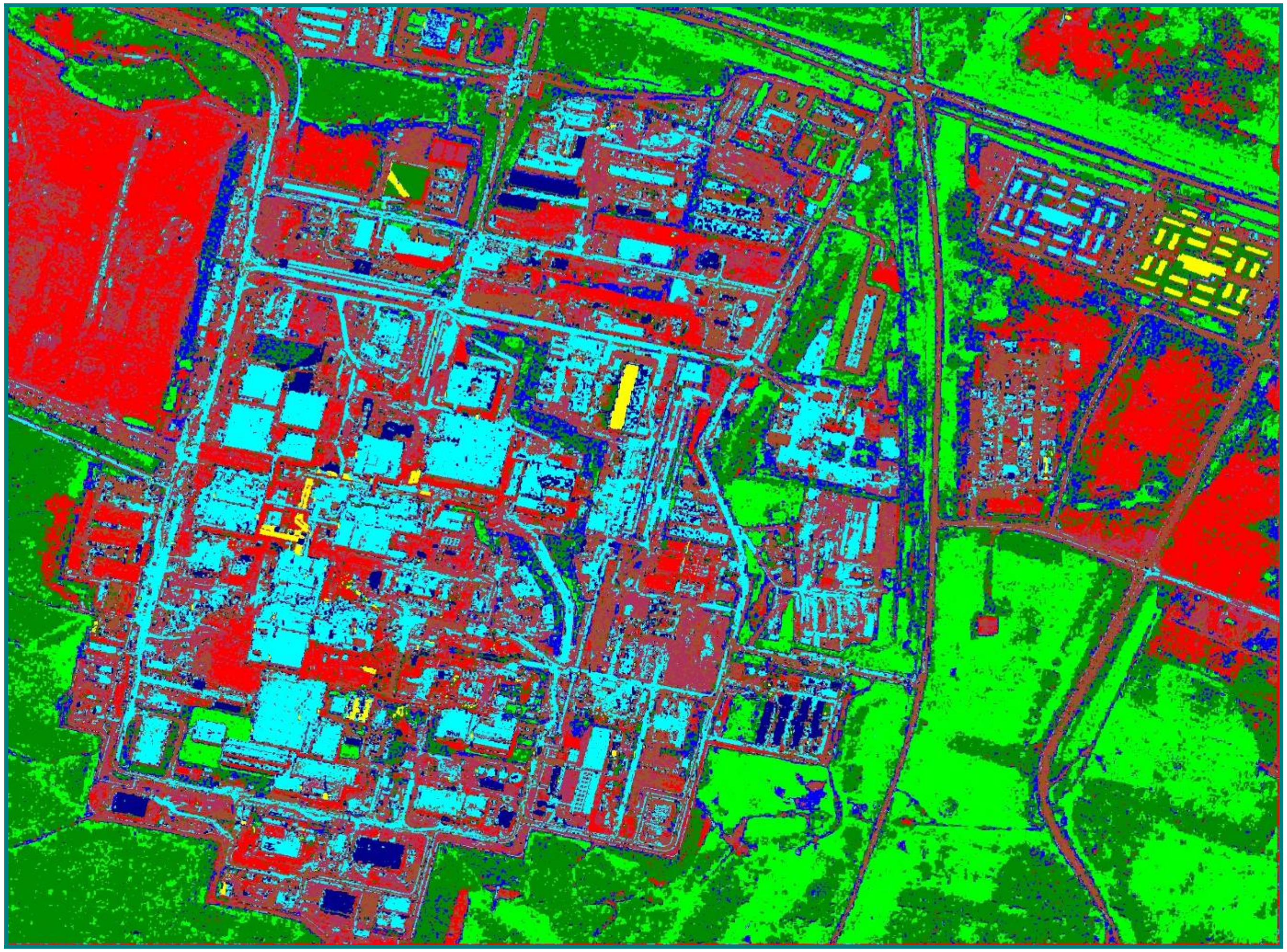

Fig. B-3. Reprocessing Plant: Gramm-Schmidt Sharpening, Cubic Convolution/Sensor Resampling, Mahalanobis Distance Classification (RGCSDO00.img).

# VITA

Alexander Solodov was born in Ozersk, Russia. He attended Ural State Technical University in Yekaterinburg, Russia and graduated with a M.S. degree in Physics in February 2001. After graduation Alexander worked as an Engineer at the Central Plant Laboratory of the Mayak Production Association in Ozersk.

Alexander was admitted to the graduate school at Texas A&M University in January 2003. Since September 2005, he has been employed by the Oak Ridge National Laboratory (Oak Ride, Tennessee) as a Post-masters Research Associate. During his appointment, Alexander has been working on various research and training projects at the International Safeguards group.

Alexander received a Doctor of Philosophy degree in Nuclear Engineering from Texas A&M University in May 2007.

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